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NOTE ON NEW ZEALAND SPECIES OF *ATOMODESMA* BEYRICH

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(Received for publication, 23 January 1959)

Summary

Atomodesma trechmanni (Marwick) is referred to *Aphanaia* de Koninck (1877) (=*Maitaia* Marwick, 1935; *Intomodesma* Popov, 1958). *A. marwicki* Waterhouse is referred to *Kolymia* Licharew (1941). *Aphanaia* and *Kolymia* are considered to be subgenera of *Atomodesma.*

INTRODUCTION

Two Permian lamellibranch species from New Zealand have been placed by the writer in *Atomodesma* Beyrich (1864), namely *A. trechmanni* (Marwick, 1934, 1935), and *A. marwicki* Waterhouse (1958). Subsequently, Mr J. M. Dickins, Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australia, has kindly drawn attention to recent Russian work which affects the systematic position of both New Zealand species. The following note summarizes these changes.

Atomodesma (Aphanaia) trechmanni (Marwick)

1934 *Maitaia trechmanni* Marwick: 948.
1935 *Maitaia trechmanni* Marwick: 295, pl. 34, figs 1-3.
1958 *Atomodesma trechmanni* Waterhouse: 171, fig. 2B (for synonomy).

Originally considered to be *Inoceramus* on account of the thick prismatic shell (Hector, 1870), this species was compared to the Australian species *Aphanaia mitchelli* McCoy by Trechmann (1917), placed in a new genus and species *Maitaia trechmanni* by Marwick (1934, 1935), and referred to *Atomodesma* by Waterhouse (1958). Waterhouse pointed out that the type species of *Atomodesma* was plicate, in contrast with the non-plicate New Zealand species, but this difference was thought to be unimportant. However, Popov (1958) has recently erected a new genus *Intomodesma* for non-plicate Russian species, and if the separation is valid, the New Zealand species must be placed with *Intomodesma*. *Intomodesma* appears to be a junior synonym of the non-plicate genus *Maitaia* Marwick (1934), which itself is apparently a synonym of *Aphanaia* Koninck (1877). Thus, *trechmanni* Marwick apparently belongs to *Aphanaia*.

The type species of *Aphanaia* is *Inoceramus mitchelli* McCoy (1847) from the Maitland Group of New South Wales, Australia. This is a relatively small species, with a single ligament groove carrying faint longitudinal striations and ridges, which probably represent growth lines. Small specimens of *trechmanni* have similar faint growth ridges on the ligament area. However, in mature specimens, which are much larger than *A. mitchelli*, the growth ridges are strongly developed, and have been previously confused with ligament grooves by Marwick (1935) and Waterhouse (1958). Unlike Myalinid ligament grooves, the growth ridges and grooves of *trechmanni* lie parallel to the hinge margin, and pass posteriorly on to the external surface of the shell, whereas the ligament grooves intersect the posterior inner margin of the hinge in Myalinid genera figured by Newell (1942). Thus *trechmanni* is larger than *A. mitchelli*, and has stronger growth-ridges, but neither difference is considered at present to be of generic or subgeneric importance. The reference of *trechmanni* to *Aphanaia* still needs to be confirmed, however, for it is not known if the New Zealand species is inequivalve like *mitchelli* (Waterhouse, 1958, p. 169).

Atomodesma (*Kolymia*) *marwicki* Waterhouse

1956 *Maitaia* Marwick in Wood, p. 38, fig. 18.

1958 *Atomodesma marwicki* Waterhouse, p. 173, fig. 2A.

Like *trechmanni*, *A. marwicki* lacks plicae, but differs in having an anterior wing. It may therefore be placed in *Kolymia* Licharew (1941), which is non-plicate, and has an anterior wing. More is now known about the occurrence of *A.* (*Kolymia*) *marwicki*. The type specimen occurs in the upper Waipahi Group, near Gore (according to Wood, 1956) and the species occurs with *A.* (*Aphanaia*) *trechmanni* in the lower Maitai Group at Nelson, in a band of fine sandstone and siltstone. This band lies below the Greville beds and above bands of limestone at the base of the Maitai Group. The statement in Waterhouse (1958) that a derived specimen came from the Te Anau rocks near Collins River is incorrect; the specimen probably came from sandy beds of the same band. Nearby specimens have been found in place by the writer near the serpentine quarry at the head of the Whangamoa River.

Genera or Subgenera?

Kolymia and *Intomodesma* (*Aphanaia*) are treated as genera by Popov (1948, 1958); here they are placed as subgenera of *Atomodesma*, with the advantage that prismatic fragments of shell, so common in the New Zealand Permian, may be referred to loosely as *Atomodesma* (*s.l.*). Undoubtedly the three form a natural group, perhaps of subfamily rank. There may be room for a fourth genus or subgenus, because the anterior ear may not be developed in all species of *Atomodesma* (*sensu stricto*). Muscle scars and details of shell structure of *Atomodesma* (*sensu lato*) have also not yet been described in detail: these could differ between species.

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NOTE ON THE OCCURRENCE OF MANGANESE IN SOUTH-EASTERN WAIRARAPA

By H. E. FYFE and J. J. REED, New Zealand Geological Survey, Department of Scientific and Industrial Research, Wellington.

(Received for publication, 10 February 1959)

Summary

Pockets of high-grade manganese ore, principally braunite, are associated with red bands of basaltic lava and jasper in Cretaceous rocks in south-eastern Wairarapa. The pockets are too small and too sporadic to be of economic importance.

INTRODUCTION

In December 1957 Mr H. Frame of Te Awaiti Station forwarded for identification a mineral sample which proved on examination to be high-grade manganese ore. The sample (P 21231*) thus provided confirmation of an earlier report of manganese in the district (Colon. Mus. and Lab. 1892, p. 35). In the company of Mr Frame the writers examined the deposit on 16 October 1958 with the results given in this paper.

LOCATION AND GEOLOGICAL OCCURRENCE

The deposits discovered by Mr Frame are near the coast about six miles north-east of Te Awaiti Station, and about half way between the mouths of the Oterei and Pahaoa rivers (Fig. 1). Manganese ore is seen as black "coatings" on red boulders of basaltic lava and jasper exposed in a stream bed (Gird. Ref. N 166/141050) in the hills which rise steeply from a wide coastal platform. Further up the stream bed the "red-rocks" with the accompanying manganese mineralization are found in place and can be traced for several chains on both sides of the stream as an apparently discontinuous band about a chain wide, intercalated with the lighter coloured Cretaceous (probably Mokoiwian) greywacke, argillite, and conglomerate that form the bulk of the rocks in the Te Awaiti district. The strike of the red band (30° E) agrees with the regional strike of the Cretaceous rocks, although contortions in the strike of the latter are prominent in the hills below the outcrops of "red-rock".

The "red-rocks" assemblage of basaltic (spilitic) lava and jasper is comparable with that found interbedded with the Triassic(?) greywackes and argillites in many parts of the Wellington district (Reed, 1957) and the association of manganese with such an assemblage is in keeping with McKay's dictum (1888), that it is with the "red-rocks"

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*Number refers to rock specimen in petrological collections of New Zealand Geological Survey.

N.Z. J. Geol. Geophys. 2 : 272-4.

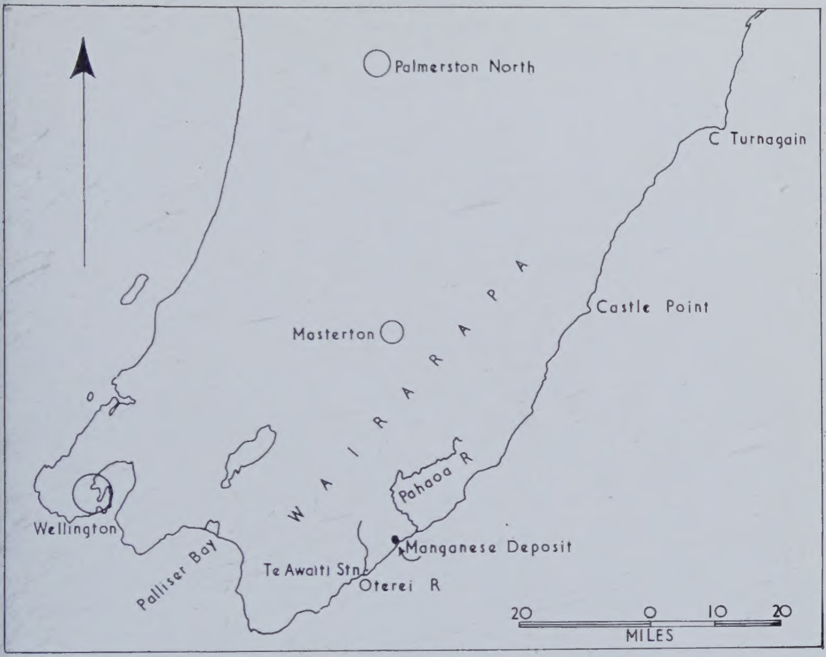

Fig. 1.—Map showing location of manganese deposit.

that "all indications of ore bodies connected with the older rocks of the Wellington Province have been found".

The absence of limonite indicates that secondary enrichment is an insignificant factor in the concentration of the manganese, which appears to owe its formation to solutions formed during the submarine extrusion or intrusion of basaltic lava. A similar origin has been proposed by Park (1946) for comparable deposits in Washington, U.S.A.

QUALITY AND QUANTITY

A chemical and spectrographic analysis of the sample (P21231) collected by Mr Frame, together with that of a sample analysed in 1892, are given in Table 1. The high grade of the ore is apparent.

X-ray examination by the Dominion Laboratory of P 21231 indicated five diffraction lines corresponding closely with the five strongest lines of braunite (Mn_7SiO_{12} or 3 Mn_2O_3 $MnSiO_3$). The laboratory also reported that other crystalline material may be present but that the patterns may be masked by a considerable amount of scattered radiation suggesting a fairly high proportion of amorphous material. That some psilomelane accompanies the braunite is indicated by the amount of barium in the spectrographic analysis.

TABLE 1.—Chemical and Spectrographic Analyses of Manganese-Ore from the Te Awaiti District.

	A	B
Total Mn	57·4	—
MnO_2	51·9	86·90
MnO	31·8	—
Fe_2O_3	—	7·21
SiO_2	—	4·01
H_2O	—	1·06
Loss	—	0·82
CaO	—	Trace
MgO	—	Trace
Si	4	
Ca	1	
Ba	0·1	
Sr	0·01	
Cr	0·005	
Mg	0·01	
V	0·02	
B	0·15	
Al	0·2	

Zn, Bi, W, Na, As, Sb, Sn, Co, Ni, Pb. Mo, Cd, Be were not detected.

A. Manganese ore (P 21231), collected by Mr H. Frame from stream bed about half way between Oterei and Pahaoa rivers (N.Z.M.S. 1, Sheet N166/141050). Analysts W. Kitts and H. J. Todd, Dominion Laboratory, D.S.I.R.

B. Manganese ore, Te Awaiti. Collected by Mr Coleman Phillips. Analysed by Colonial Analyst (Colon Mus. and Lab. 1892, p. 35).

Field investigation showed that the manganese ore is confined to pockets or coatings about a yard or two long and with a maximum thickness of 18 inches. These pockets are sporadically distributed through the "red-rock" assemblage and in places are associated with hematite layers. The clearest indication of quantity is given by the small proportion of manganese in the boulders of "red-rocks" in the stream bed.

It is concluded that the manganese pockets are too small and too sporadic to be economic.

ACKNOWLEDGEMENTS

The writers desire to thank Mr H. Frame for pointing out the deposits in the field and to express their appreciation of the hospitality extended by Te Awaiti Station.

Acknowledgement is made of chemical, spectrographic, and X-ray data provided by officers of the Dominion Laboratory.

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THE TERTIARY GEOLOGY OF THE PAREORA DISTRICT, SOUTH CANTERBURY

By H. S. GAIR, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 7 October 1958)

Summary

The marine Tertiary rocks in the Pareora district are about 1,500 ft thick and range in age from ?upper Dannevirke Series to Awamoan. They are underlain and overlain conformably by two sets of coal-measures, each about 200 ft thick, but only the lower contains potentially workable lignite seams. The upper coal-measures of probable Southland age are overlain disconformably or with slight angular unconformity by 600 ft of non-marine, weathered, greywacke gravels (of probable Waitotaran age) which have been folded and faulted together with the underlying Tertiary rocks. These tilted gravels are overlain unconformably by flat-lying, high-level gravels of Pleistocene age.

The Tertiary rocks are in fault contact with the greywacke and argillite of the Hunters Hills on the west, the fault having a throw of about 4,000 ft. The little evidence available suggests that this is a reverse fault. Between the Hunters Hills and the sea the Tertiary rocks have been folded into an asymmetrical anticline of which the steep western limb passes into a fault to the north.

It is suggested that, because the Waitotaran gravels were deposited while the Kaikoura Orogeny was in progress, they are thickest over the structural lows and thinnest over the structural highs, and that, depending on the amount of erosion prior to their deposition, they may overlie any of the Tertiary formations and possibly even the greywacke undermass.

PREVIOUS GEOLOGICAL INVESTIGATIONS

The area described lies to the east of the Hunters Hills, and between the Pareora and Otaio rivers (Fig. 1).

Many geologists have visited and written about the area, but only one detailed survey, that of Gudex (1918), has been carried out.

The first geologist to visit the district was W. Mantell (1850) who traversed the coastal part on his journey from Christchurch to Dunedin in 1848. He mentioned the presence of a vesicular volcanic rock at Timaru and stated that he was informed that a bed of coal, ten feet thick, cropped out on the banks of a stream inland of Timaru.

Haast (1865) examined the country between Mt. Horrible and Timaru, and the banks of the Pareora River, with a view to obtaining a water supply for Timaru. He correlated the Tertiary sequence with the Curiosity Shop beds, and stated that there were several flows of basalt some of which were intercalated with the marine beds. In his "Geology of Canterbury and Westland", Haast includes a cross-section from the Hunters Hills across the Upper Pareora basin to the coast.

N.Z. J. Geol. Geophys. 2 : 265-96.

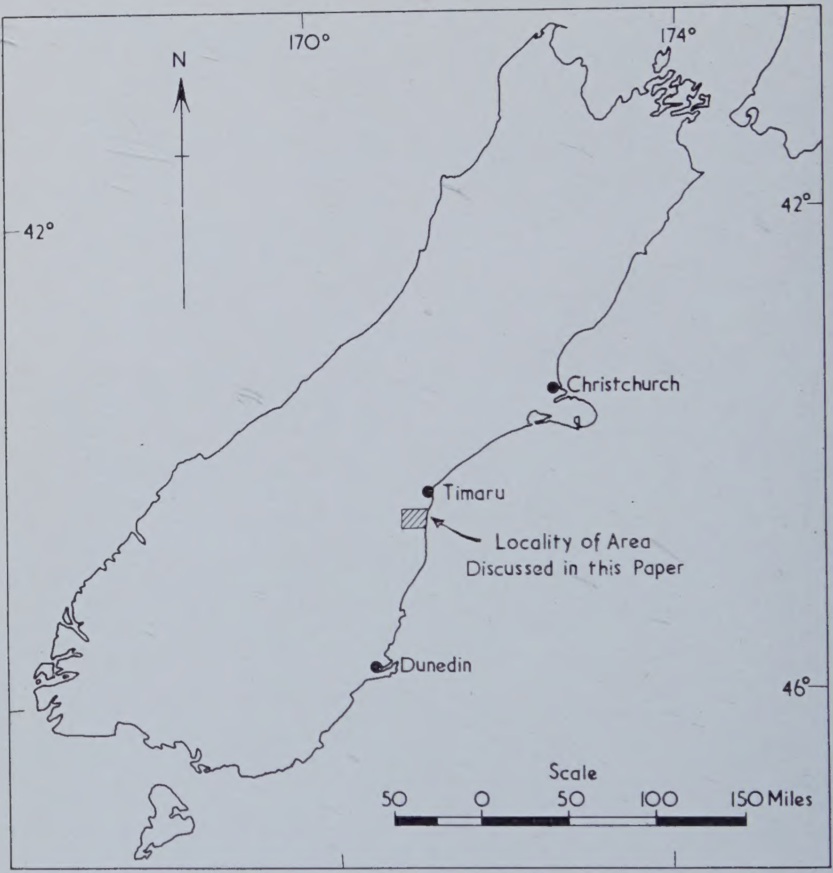


FIG. 1.—Locality map.

McKay (1877) described the succession and drew a section from north-west to south-east.

Park (1905) considered the sections at the lower and upper ends of the Pareora Gorge as too obscure to be of value for determination of the relations between the beds containing the "Pareora Fauna" and the Oamaru limestone, and stated that the fossiliferous clays and sandstones exposed at White Rock River rest on the basement rock of the district.

Hardcastle (1908) published a booklet on the geology of South Canterbury, in which the stratigraphy of the Tertiary rocks was dealt with from the point of view of climate. He held that the gravels beneath the Mt. Horrible basalt represented an earlier glacial age than the loess which overlies the basalt.

Thomson (1914) concluded that in South Canterbury and Otago there are not two limestones separated by beds with the "Pareora Fauna" as Park in 1905 supposed, but one limestone separating two sets of beds with the "Pareora Fauna", and suggested that these two similar faunas must show some difference when carefully examined.

Marshall (1916) described a specimen of the lower argillaceous limestone of the Otaio Gorge, and, arguing from the presence in it of *Amphistegina*, correlated it with the Amuri Limestone. Thomson in 1917 disputed this correlation, firstly on the grounds that *Amphistegina*, on Marshall's own showing, ranges from Upper Eocene to the present, and secondly, on the grounds that the Otaio Limestone overlies rocks with an Oamaruian fauna, while the Amuri Limestone everywhere overlies rocks with a Cretaceous fauna and contains a lower Oamaruian fauna in its uppermost part, as in the Castle Hill basin.

Gudex (1918) made a detailed survey of the area between the Pareora and Otaio rivers more from the point of view of the stratigraphy than of the structure and geomorphology. He summarized his conclusions as follows: "My examination of the district shows that the Tertiary beds of the district are all conformable, and not separable into two unconformable groups as McKay supposed; that the upper beds with a 'Pareora Fauna' are above the limestone, and not below it as Park supposed; and that there is a similar fauna above and below the limestone, as Thomson suggested. I agree further with Thomson that the lower chalky limestone of the Otaio River is not the correlative of the Amuri Limestone, but represents a higher horizon."

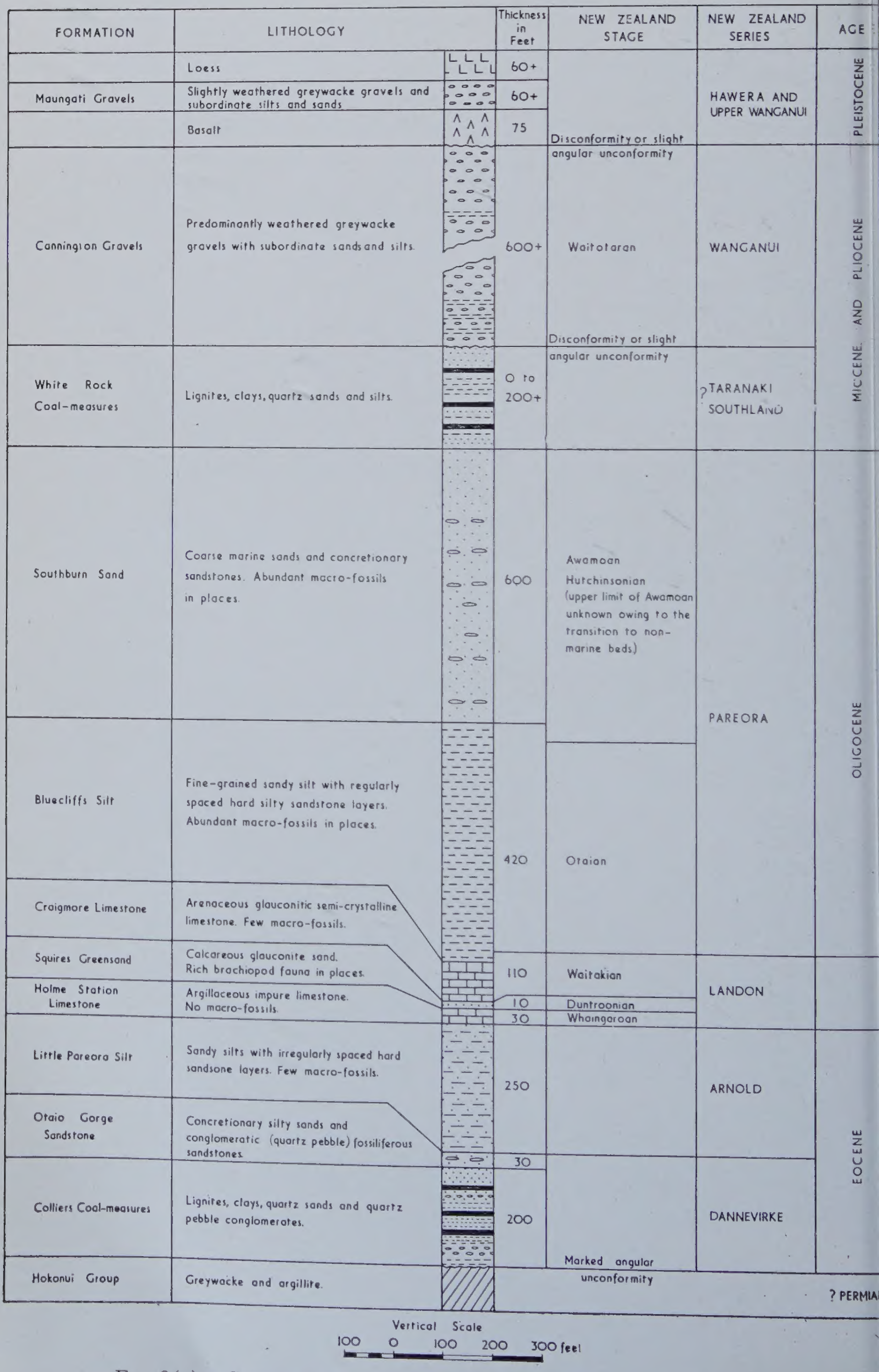
Thomson (1926) observed in the lower Pareora Gorge a phosphatic contact between a glauconitic limestone above and a chalky limestone below. He described the bored surface between these beds as similar to that between the Weka Pass and the Amuri Limestones and thought it probable that the phosphatic horizons in the Waihao, Pareora, and Totara-Raincliff districts represented the same horizon.

Laws (1933) described new Tertiary Mollusca from the Timaru district and correlated the White Rock River and Holme Station faunas with that at Sutherlands, which he considered to be of Awamoan age.

Maling (1933) compared the Tertiary sequences in the Kakahu and Pareora districts and found them to be very similar save for the absence of the blue clays, which were not recognized in the Kakahu district.

Finlay and Marwick (1947), in their paper on new divisions of the Upper Cretaceous and Tertiary, inserted, as a new division of the Tertiary, an Otaian stage based on the blue silts in the Otaio River at Bluecliffs. They defined the stratigraphic limits of this stage on both Foraminifera and Mollusca.

Ulrich (1947) made a geomorphic study of the Pareora River. The presence of Tertairy rocks in Mt. Nessing basin was mentioned, and this landform was recognized as a tectonic basin. Mt. Nessing was described as a tilted block and evidence for the presence of a fault at the Upper Pareora Gorge was presented.



FORMATION	LITHOLOGY	Thickness in Feet	NEW ZEALAND STAGE	NEW ZEALAND SERIES	AGE
	Loess	60+		HAWERA AND UPPER WANGANUI	PLEISTOCENE
Maungati Gravels	Slightly weathered greywacke gravels and subordinate silts and sands	60+			
	Basalt	75	Disconformity or slight angular unconformity		
Cannington Gravels	Predominantly weathered greywacke gravels with subordinate sands and silts.	600+	Waitotaran	WANGANUI	MIOCENE AND PLIOCENE
White Rock Coal-measures	Lignites, clays, quartz sands and silts.	0 to 200+	Disconformity or slight angular unconformity	?TARANAKI SOUTHLAND	
Southburn Sand	Coarse marine sands and concretionary sandstones. Abundant macro-fossils in places.	600	Awamoan Hutchinsonian (upper limit of Awamoan unknown owing to the transition to non-marine beds)	PAREORA	OLIGOCENE
Bluecliffs Silt	Fine-grained sandy silt with regularly spaced hard silty sandstone layers. Abundant macro-fossils in places.	420	Otaian		
Craigmore Limestone	Arenaceous glauconitic semi-crystalline limestone. Few macro-fossils.	110	Waitakian	LANDON	
Squires Greensand	Calcareous glauconite sand. Rich brachiopod fauna in places.	10	Duntroonian		
Holme Station Limestone	Argillaceous impure limestone. No macro-fossils.	30	Whaingaroan		
Little Pareora Silt	Sandy silts with irregularly spaced hard sandsone layers. Few macro-fossils.	250		ARNOLD	EOCENE
Otaio Gorge Sandstone	Concretionary silty sands and conglomeratic (quartz pebble) fossiliferous sandstones.	30			
Colliers Coal-measures	Lignites, clays, quartz sands and quartz pebble conglomerates.	200	Marked angular unconformity	DANNEVIRKE	
Hokonui Group	Greywacke and argillite.				? PERMIA

Fig. 2(a).—Composite Stratigraphic Column for the Pareora District

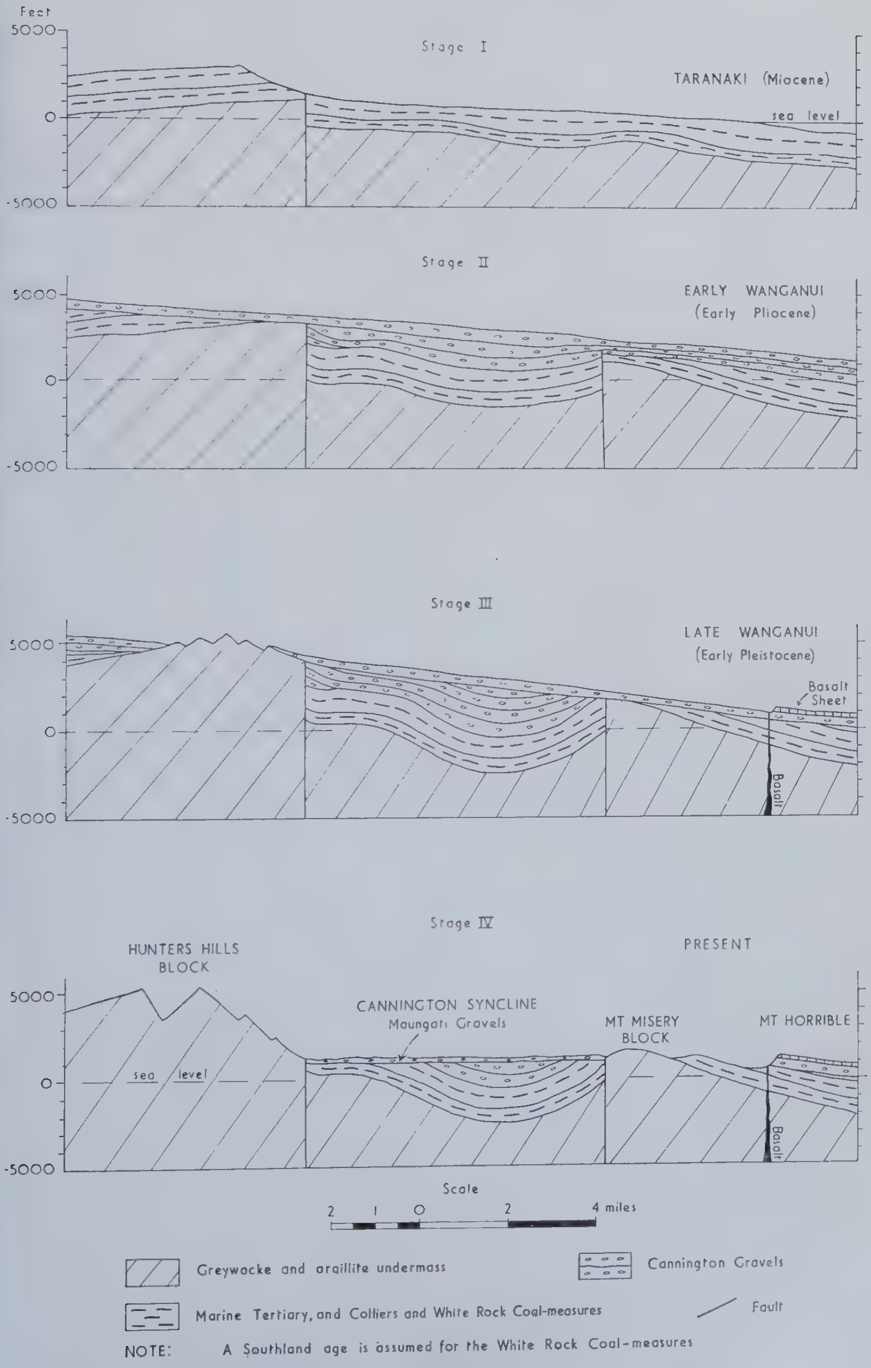


FIG. 2(b).—East-west diagrammatic sections across the Pareora District in Post-Southland time.

Raeside (1948) discussed recent changes of climate in South Canterbury and showed that the most recent change was from a warm pluvial to a cooler and drier climate.

STRATIGRAPHY

Pre-Tertiary Rocks

These consist of greywacke and argillite with minor associated beds of conglomerate and quartzite. The greywacke, and less commonly the argillite, are seamed with anastomosing quartz veins up to a few inches in thickness. In the rivers draining the Hunters Hills a few pebbles of jasper and a calcareous siltstone occur and low rank schistose rocks are exposed in the Otaio and Lower Pareora gorges.

In three localities Tertiary rocks rest upon a residual clay up to 7 ft thick which is the result of kaolinisation of the feldspar in the greywacke. At Mt. Nessing, the feldspars have not been completely kaolinised, and the greywacke, although softened almost to clay has not lost its blue colour. At Maungati in both north and south branches of the Little Pareora River, and in the north branch of the Little Pareora at the foot of the Hunters Hills, kaolinisation is more complete and the greywacke has been altered to soft white sandy clay.

The clays derived from kaolinised greywacke can usually be distinguished from those of the overlying coal formation by the presence in the former of occasional quartz veins.

Tertiary Sequence

As is usual, the Tertiary rocks overlie the greywacke and argillite undermass with marked angular unconformity.

In the composite stratigraphic column for this area (Fig. 2(a)) it will be noted that the writer has distinguished two formations additional to those of Gudex (1918)—an upper coal formation, and a thick sequence of tilted greywacke gravels and silts. The latter is similar in occurrence and character to the Kowai Gravels of North Canterbury and is probably its correlative.

The sequence represents a marine transgression and regression due to depression and subsequent uplift of the area, and at only one contact is there any indication of a break in deposition of the marine beds. This is the bored surface between the argillaceous limestone and the calcareous greensand, and may not represent a significant time interval.

(1) COLLIERS COAL-MEASURES

Type Locality: Otaio River Gorge. Sheet S 118.
Grid Ref. 504365.

In most localities the lowest bed of this formation is a white plastic-clay up to 5 ft thick. This is overlain by a succession of white and black (carbonaceous-stained) quartz sands, quartz-pebble gravels and conglomerates (mostly well-rounded but some angular), grits, clays, and micaceous shales up to the first coal seam which is about 50 to 70 ft from the base. Pyritic concretions are common in the beds beneath the coal seams and are particularly abundant in some of the clays. The coal appears to be best developed along the base of the Hunters Hills, where as many as ten seams have been observed—elsewhere it is represented by thin carbonaceous layers, as at Maungati. The coal is of lignite rank and is in seams up to 5 ft thick (but mostly less than 1 ft) which are interbedded with quartz grits and sands stained by iron and carbonaceous material. Above the lignites are about 100 ft of unconsolidated quartz sands, and a few quartz pebble conglomerates and gravels predominantly white in colour. No marine fossils were obtained from these beds and it is concluded that they are all continental deposits.

(2) OTAIO GORGE SANDSTONE

Type Locality: Otaio River Gorge. Sheet S 118.
Grid Ref. 505366.

The coal formation is overlain by rust-brown coloured, current-bedded, fossiliferous, silty sands that contain sandstone concretions up to 5 ft in diameter, and cemented conglomeratic (rounded quartz pebbles about ½ in. in diameter) concretionary layers up to 3 ft thick. The concretionary layers contain abundant molluscan faunas which Dr J. Marwick (pers. comm.) has tentatively classed as upper Dannevirke Series. There is a good exposure of these hard, conglomeratic concretionary layers about 300 yards downstream from the junction of the north and south branches of the Little Pareora River at Maungati.

(3) LITTLE PAREORA SILT

Type Locality: Little Pareora River, Maungati.
Sheet S 110. Grid Ref. 536444.

Although Gudex (1918) refers to this formation as "the crab-beds and marls" the writer found only one fossil crab and was unable to distinguish the upper members as marls. In a few places difficulty is experienced in separating hard sandstone layers near the base of the Little Pareora Silt from similar beds in the underlying concretionary sands and conglomerates; the presence of layers of simple corals (*Balanophyllia hectori* Tenison-Woods) in such sandstones places them with the Little Pareora Silt.

The formation consists predominantly of blue-grey sandy silts with irregularly distributed hard sandstone bands commonly 1 ft thick. These beds weather to rust brown colours. Small, hard, rounded, argillite pebbles about $\frac{1}{10}$ in. in diameter occur sparingly throughout but are more common in the top half of the formation. In general the beds become less sandy towards the top where they grade into the Holme Station Limestone. Some parts of the middle and upper members are moderately glauconitic, and the middle portion contains gypsum in small discontinuous films mostly at right-angles to the bedding planes. Fossil resin is common both in this formation and in the underlying Otaio Gorge Sandstone. No micro-faunas were obtained and the Mollusca were in such a poor state of preservation that collecting was not attempted.

(6) CRAIGMORE LIMESTONE } Type Locality:
(5) SQUIRES GREENSAND } D. Squire's farm.
(4) HOLME STATION LIMESTONE } Sheet S 118. Grid Ref. 496376.

The occurrence of an upper arenaceous glauconitic semi-crystalline limestone, separated by an impersistent layer of calcareous glauconite sand from a lower argillaceous almost chalky limestone with a bored surface and is typical of much of Canterbury (see Fig. 3). The upper arenaceous limestone in the Pareora District (Craigmore Limestone) is almost identical in appearance with the Weka Pass Stone of North Canterbury, and the lower argillaceous limestone (Holme Station Limestone) very closely resembles the Amuri Limestone of the Middle Waipara District. Samples of the Craigmore Limestone from a lime quarry on Frenchman's Gully road ranged from 80·2% $CaCO_3$ to 93·75% $CaCO_3$, and samples of the Holme Station Limestone from the lower Pareora Gorge contained 63·5% $CaCO_3$ and 58% $CaCO_3$ respectively. The lower argillaceous limestone is massive, with the typical subconchoidal fracture of mudstone, and the upper part is slightly glauconitic, the grains of glauconite being much smaller than in the overlying glauconite sand and semi-crystalline limestone. The depth of the bored zone varies from 6 in. to 3 ft and the borings are filled with the overlying calcareous glauconite sand (Squires Greensand). The latter varies considerably in glauconite content and hence in colour. In places the greensand consists of mostly unconsolidated, current-bedded, glauconite sand, but usually it is more calcareous than glauconitic and there is a progressive increase in hardness with increase of calcium carbonate. About 6 in. to 12 in. above the base of the greensand is a single layer of phosphatic nodules up to 9 in. across, but most commonly only $\frac{1}{2}$ to 1 in. in diameter. Usually the nodules appear as a line of small pebbles projecting from the surface of the greensand, and in places they are so abundant that they form an almost continuous layer. By a gradual increase in calcium carbonate content the greensand merges imperceptibly with the overlying semi-crystalline glauconitic limestone (Craigmore Limestone). This limestone is mostly regularly stratified in hard

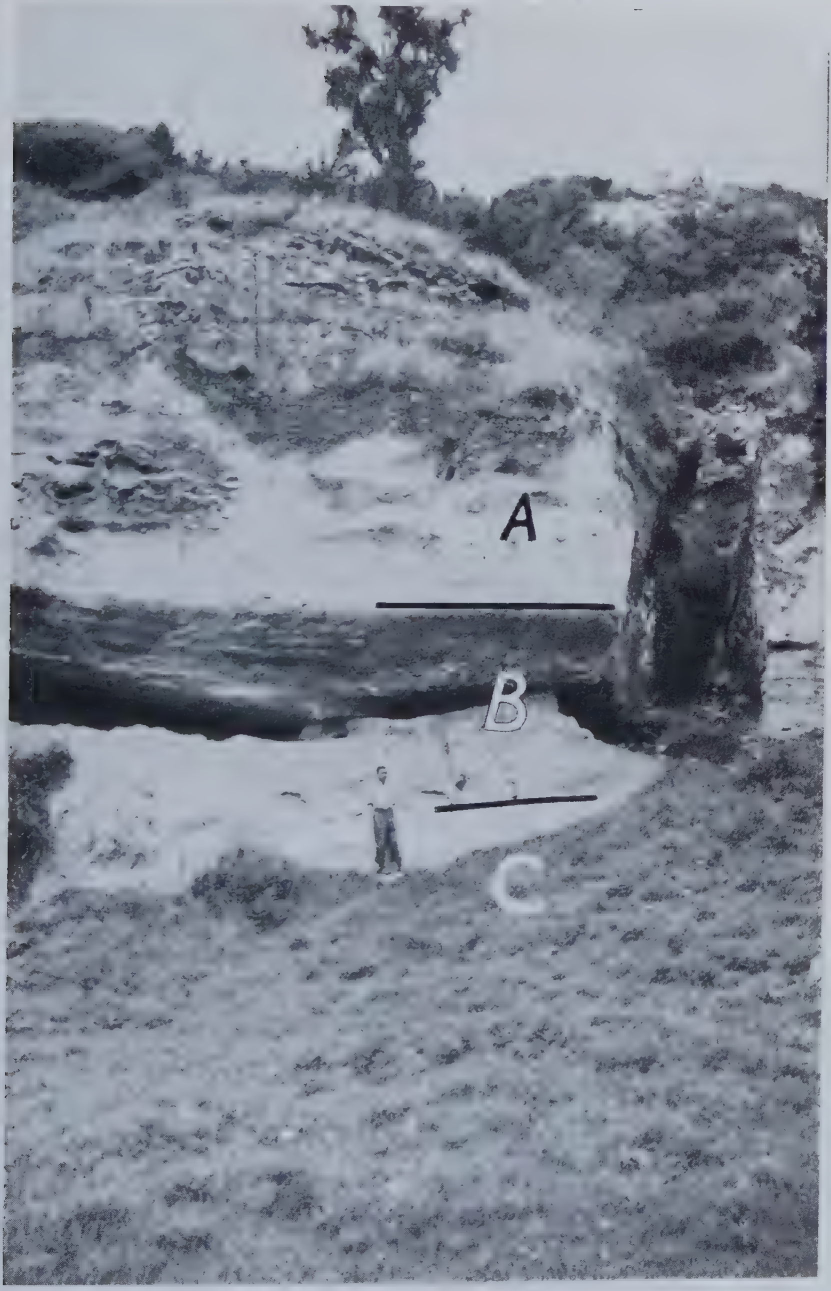


FIG. 3.—Craigmore Limestone (A), Squires Greensand (B), and Holme Station Limestone (C). (D. Squires' farm.)

and soft layers, which give it a fluted surface on weathering. The lower half of the limestone is current-bedded on a small scale. The lowest twenty or so feet in most places is unstratified and in the middle portion hard bands are spaced 9 in. to 1 ft apart, becoming further apart towards the top of the limestone.

FAUNAS: Holme Station Limestone contains no macrofossils, but good foraminiferal faunas of Whaingaroan age were obtained.

Squires Greensand contains a rich brachiopod fauna (the typical *Liothyrella landonensis* fauna) together with Pecten occasional Echinoderm spines and shark teeth, and fair Foraminifera faunas, all of which indicate a Dunrtoonian age.

Craigmore Limestone contains Echinoderm fragments, Pecten, and shark teeth, and typical microfaunas of Waitakian age. The change from Waitakian to Otaian faunas occurs within the lowermost few feet of the overlying Bluecliffs Silt.

(7) BLUECLIFFS SILT

Type Locality: Bluecliffs, Otaio River.
Sheet S 111. Grid Ref. 575404.

The arenaceous semi-crystalline limestone passes gradually up into a blue sandy silt ("Blue clay" of Gudex) in which hard sandstone layers 5 ft to 6 ft apart and about 1 ft thick give a very regularly banded appearance. The silt is fossiliferous throughout, but more so in the middle and upper portions, the macrofossils being chiefly Mollusca with a few brachiopods near the base. Pyritic concretions occur irregularly throughout, and gypsum in small films is widely distributed. This formation constitutes the Otaian stage.

(8) SOUTHBURN SAND

Type Locality: Southburn Cutting, Otaio River.
Sheet S 119. Grid Ref. 597393.

The Bluecliffs Silt grades up into brown-coloured sands and sandstones, first by a change of colour from a blue-grey to a brown silt, then a textural change from silt to sand. Sandstone layers, commonly 2 ft thick and spaced about 5 to 10 ft apart, and concretions up to 5 ft in diameter, occur throughout almost the whole of the Southburn Sand. Well preserved Mollusca occur in profusion in or adjacent to the sandstone layers and concretions. These and Foraminifera date the formation as ranging in age from Hutchinsonian to Awamoan.

(9) WHITE ROCK COAL-MEASURES

Type Locality: White Rock River.
Sheet S 110. Grid Ref. 490553.

The White Rock Coal-measures and the overlying Cannington Gravels together constitute the Pareora Gravels as defined originally by McKay (1882, p. 100) and Hector (1882, p. 25).

White Rock River and the Pareora River about three miles below the upper gorge are the only localities where this upper coal formation is exposed. Only one shaly lignite seam and about 40 ft of white and grey quartz sands are exposed in the Pareora River, where there appears to be a greater disconformity with the overlying Cannington Gravels, but at White Rock River some ¾ mile upstream from its junction with the Pareora at least 200 ft of the upper coal formation is exposed. There, the underlying Southburn Sand grades upwards into black (carbonaceous-stained) quartz sand which in turn is overlain by two 4 ft lignite seams separated by a 4 ft bed of carbonaceous shale. Veins of gypsum up to ½ in. thick occur throughout the lignite, particularly along bedding planes. The lignites are exposed again in a small syncline about 3 miles farther upstream. The lignites, clays, and shales of the coal-measures are overlain by several hundred feet of sands, silts, and greywacke conglomerates of the Cannington Gravels and the dip increases from 27° at the lignites to 67° at the top of the Cannington Gravels. The clays and shales associated with the coal formation range in colour from blue to grey-white and thus can be distinguished from the predominantly yellow-coloured clays of the overlying Cannington Gravels. Plant microfossils from the White Rock River section indicate a Southland age for the White Rock Coal-measures.

(10) CANNINGTON GRAVELS

Type Locality: Left bank, Pareora River, Cannington.

Sheet S 110. Grid Ref. The terrace extending from 468598 to 510569.

Overlying either the White Rock Coal-measures or the Southburn Sand, disconformably or with slight angular unconformity, is a succession of non-marine, weathered greywacke gravels, silts, and clays that have been faulted together with the underlying Tertiary beds, They are particularly well developed at Cannington, which is their type locality, and are exposed also at White Rock River, Maungati, and south-west of Maungati to the west of the Maungati Fault. In the type locality the Cannington Gravels constitute the high plateau which forms the northern boundary of Cannington basin, and good exposures occur in the badland gullys along the southern edge of this plateau overlooking Cannington basin (see Fig. 4). The gravels have been folded into a gentle syncline (dips of up to 10°) at the western limb of which they overlie about 15 ft of White Rock Coal-measures.

At Maungati the Cannington Gravels occur in an asymmetrical syncline, the steep eastern limb of which (dip 60°—see Figs 5 and 6) has been faulted against Colliers Coal-measures overlying greywacke. In south-west Maungati the Cannington Gravels are exposed at several places along Cabbage Tree Point road, and in a road-cutting about 300

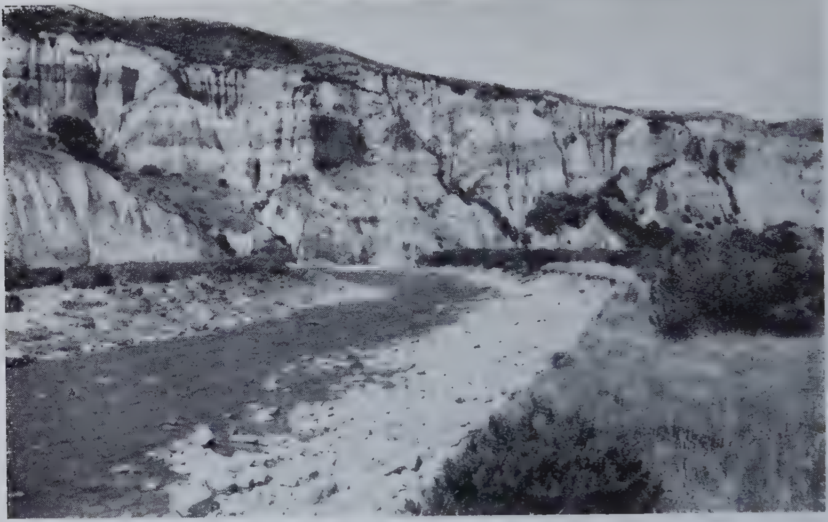


FIG. 4.—Cannington Gravels, type locality, Cannington. Note the slight dip upstream (to the left).

yards from the junction of this road with the road on the north side of the Otaio River, is an exposure of very weathered, steeply dipping Cannington gravel and silt overlying fossiliferous Southburn Sand. The Cannington Gravels can be distinguished from younger gravels by the following criteria:

(1) They are usually (but not necessarily) inclined. In the absence of other evidence, gravels and silts dipping upstream (however slightly) are likely to be Cannington Gravels.

(2) The greywacke pebbles are on the whole considerably weathered and many can be crushed by hand.

(3) They are usually more cemented, mostly by iron oxides, and hence are commonly rust-red in colour.

(4) They contain more silt and sand layers than do younger beds, particularly in the lower and middle portions.

(5) A few of the silts and silty clays contain fragmentary plant remains which have not been found in Pleistocene and Recent gravels.

AGE: The discovery by Mr J. D. Raeside in 1946 (Collins, 1953) of Waitotaran marine fossils in weathered greywacke gravels, of similar occurrence and character to the Cannington Gravels, in the Makikihi River about 9 miles south of the Pareora District, strongly suggests that the Cannington Gravels are also of Waitotaran age and thus the correlative of the Kowai Gravels of North Canterbury.

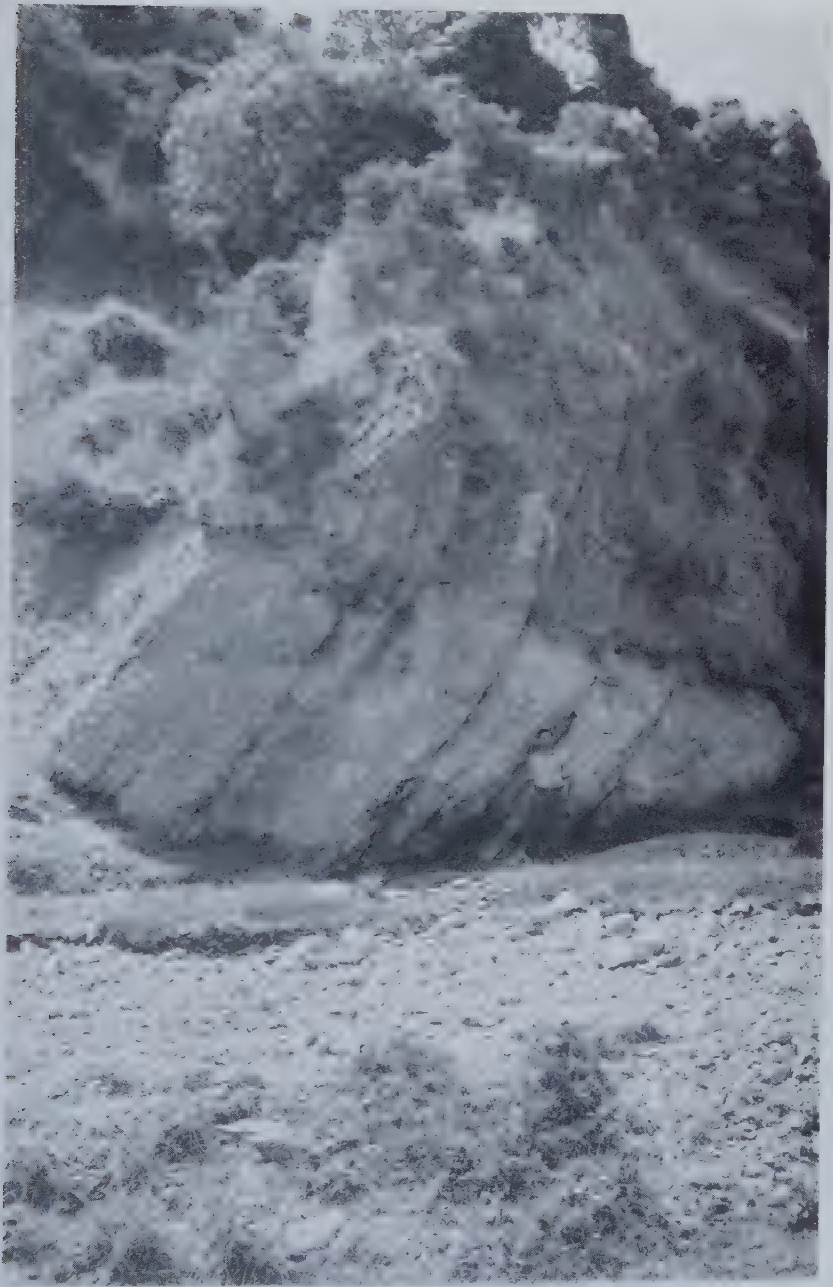


FIG. 5.—Cannington Gravels dipping at about 60°. South branch of the Little Pareora River, Maungati. At the type locality for the Maungati Gravels.

Quaternary Deposits

Pleistocene gravels, sands, and silts are far more widespread than Recent deposits, which are almost restricted to the present flood plains of the rivers. For the old flat-lying gravels and silts that overlie unconformably the Cannington Gravels at Maungati (see Fig. 6), the term *Maungati Gravels* is proposed.

The youngest Pleistocene deposit is a fine-textured, yellow loess which forms a capping of variable thickness over much of the area. Directly beneath the basalt at Mt. Horrible is an 18 in. layer of orange-yellow coloured, banded tuff overlying a fossil soil formed on yellow silt. The presence of tuffaceous beds beneath the basalt was first reported by Haast (1865, p. 7 and map).

(11) MAUNGATI GRAVELS

Type Locality: Left bank terrace of the Little Pareora River.
Sheet S 110, Grid Ref. 534435.

The Maungati Gravels are similar in lithology to Cannington Gravels but they are not tilted, and are on the whole less weathered and less cemented and contain fewer sands and silts. Because of this similarity in lithology it is very difficult to assign "old" high level terrace gravels to either the Maungati or Cannington formations, in fact only in exposures that show two sets of "old" gravels separated by an unconformity can the Maungati Gravels be identified with certainty.

STRUCTURE

Three major structures can be distinguished in the Pareora district.

Hunters Hills block, including Mt. Nessing basin.

Cannington syncline.

Craigmore anticline—Mt. Misery block.

Hunters Hills block, including Mt. Nessing basin

This block is elongated in a northerly direction, and the strike of the greywacke and argillite comprising it is also northerly. It is separated from the Tertiary rocks to the east by a major fault with a throw of about 4,000 ft. In general the dip of the Tertiary rocks increases from about 10° to as much as 40° within a few hundred yards of this fault. Tertiary beds in fault contact with greywacke or argillite can be observed at three places along the foot of the Hunters Hills. At the Upper Pareora Gorge the Craigmore Limestone is intensely shattered and shows fault drag (see Fig. 7). From here the direction of the fault can be accurately traced to the south since in three of the

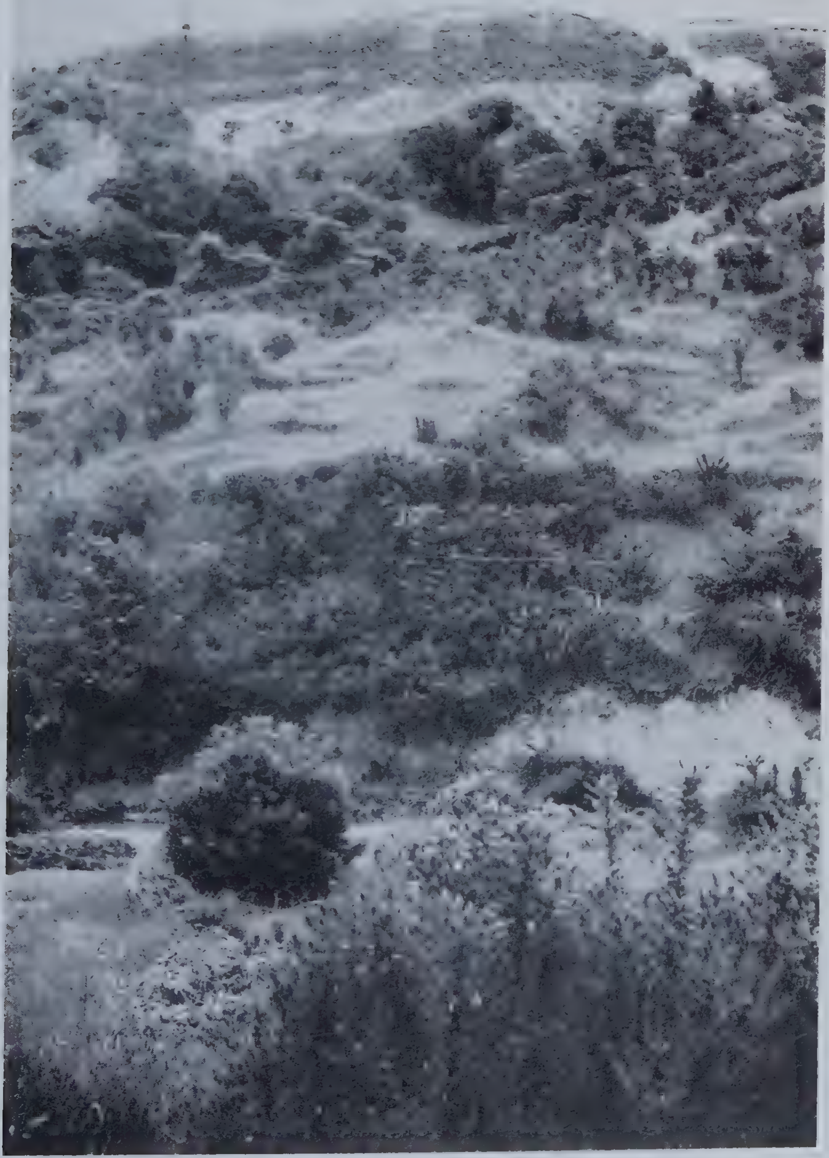


FIG. 6.—Cannington Gravels, dipping at about 25° and overlain by horizontal Maungati Gravels. Type locality for the Maungati Gravels, Maungati.

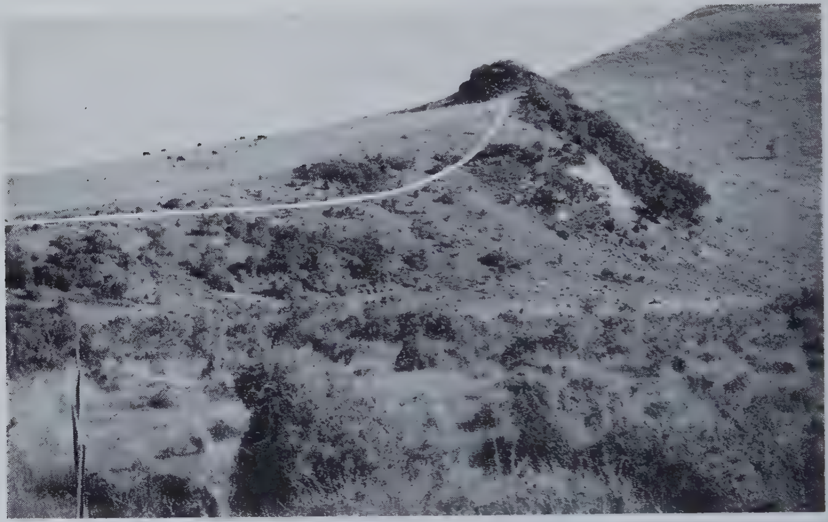


FIG. 7.—Craigmore Limestone in fault contact with greywacke and showing fault drag. Upper Pareora Gorge.

valleys between the Upper Pareora Gorge and White Rock River the limestone may be observed in proximity to greywacke. The other two exposures of the fault contact are to be seen in the Motukaika River just below Green's farm on the back road of the Hunters Hills. There argillite has been intensely shattered for a distance of 20 yards from the fault plane, and Tertiary rocks have been affected by small subsidiary faults for a similar distance on their side of the main fault. The upstream exposure is directly below the farmhouse in the right bank of the river and shows quartz grits and sands of Colliers Coal-measures in fault contact with argillite. At the contact is a 3 in. to 5 in. layer of white-, blue-, and black-streaked, extremely plastic fault gouge. The quartz grits and sands are apparently faulted against a wedge of Squires Greensand which is in turn faulted against Bluecliffs Silt. None of the beds in this fault zone shows stratification, and the subsidiary fault planes are not clearly defined, which suggests that flowage has occurred. At the second exposure, some 150 yards downstream, there is a fault wedge of pulverized argillite about 6 ft wide which has Tertiary rocks on both sides. The fact that the fault planes of these subsidiary faults and of the main fault all dip towards the Hunters Hills at 60° to 80° indicates that the fault is probably reverse.

From the Motukaika River the throw along the Hunters Hills Fault decreases to the south as in the north branch of the Little Pareora River at W. Squire's farm, and in the Otaio River section Colliers Coal-measures occur in proximity to greywacke.

MOUNT NESSING BASIN

There are no Tertiary outliers within the Hunters Hills, but north-north-east of Mt. Nimrod a large fault splinter of greywacke departs from the main range in this direction, and between it and the main range is a narrow strip of Tertiary rocks preserved in the fault angle depression (Mt. Nessing Basin). The fault splinter pitches to the north the greywacke disappearing beneath Tertiary marine sands at the Opawa River. The fault forming the western boundary of Mt. Nessing Basin can be observed in the northern extremity of the "badland gully" in the left bank of the north branch of the Pareora River. Marine sands of probable Arnold age (see Fossil Localities) are faulted against argillite which is extremely shattered for at least 30 ft from the fault contact. The fault plane is very irregular here and dips from 30 to 70° to the west, which indicates that the fault is also of the reverse type. It is possible that on the eastern side of the southern extremity of Mt. Nessing Basin there is a small fault of only a few feet throw, as a greywacke terrace rises very abruptly from within a few yards of Tertiary sands exposed in the bed of the Pareora River.

Cannington Syncline

Cannington Basin has been eroded along part of an asymmetrical syncline of Tertiary sediments which is cut off on the west by the Hunters Hills Fault, and bounded on the east by Mt. Misery block and Craigmore Anticline. At the northern and southern extremities of the basin, Cannington Gravels form the axis of the syncline and occur as high-level, slightly dissected terraces which form a natural geographic boundary. There are two minor anticlines bordering this basin on the west and cut off by the Hunters Hills Fault. These are the small anticline at D. Squire's farm and the more extensive Upper Pareora Gorge anticline, both of which trend at right-angles to the Cannington syncline.

Craigmore Anticline—Mt. Misery Block

Craigmore Anticline is an asymmetrical fold with its steeply dipping limb on the north-west side. The surface of the Craigmore Limestone, which forms the crest and limbs of the anticline, is pitted with numerous sink-holes (see Fig. 8). At the Lower Pareora Gorge the trend of Craigmore Anticline changes from north-east to north-north-west, and the steeply dipping western limb passes into a fault to form the Mt. Misery tilted undermass block. Tertiary rocks have been stripped from the upper slopes of the blackslope of Mt. Misery block to reveal a flat fossil plain surface (probably part of the pre-Tertiary peneplain). At the foot of the Mt. Misery exhumed "fossil" fault scarp near the Pareora River is a small terrace of greywacke probably formed by step-faulting. In the south-west, the Craigmore Anticline is cut off by a fault (the Maungati Fault) which is exposed in the left bank of the southern branch of the Little Pareora River at Maungati. The exposure shows steeply-dipping Cannington Gravels underlain by the Southburn Sand, both of which dip at 65° to the west, faulted against flat-lying Colliers Coal-measures which overlie greywacke.

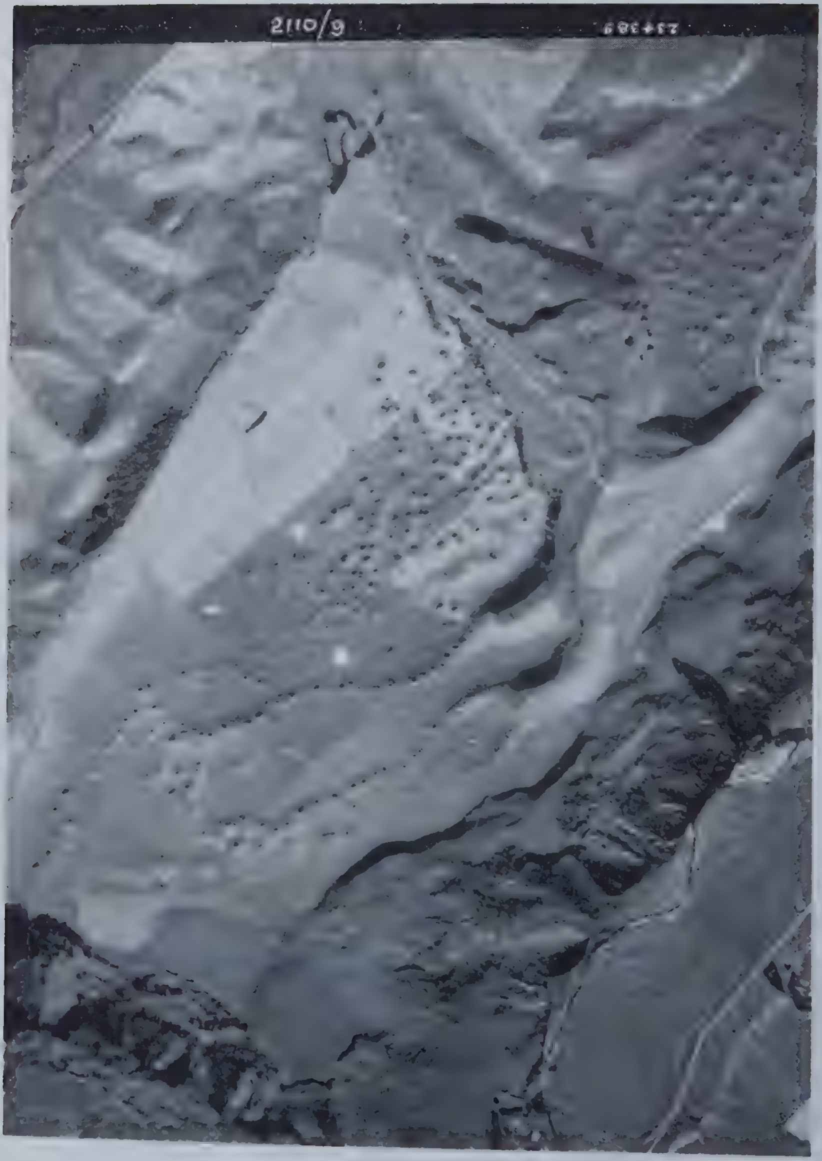


FIG. 8.—Sink holes in the Craigmore Limestone along the crest of Craigmore anticline. Note also the slump topography (on the Little Pareora Silt) in the south-east corner of the photograph to the north-west of the Little Pareora River (lower right). (Photo reproduced by permission of Lands and Survey Department.)

GEOLOGICAL HISTORY

The remnants of an exhumed fossil peneplain which rise from beneath the cover of Tertiary sediments on the back slope of Mt. Misery block and Mt. Nessing fault splinter are probably part of the widespread, pre-Tertiary peneplain cut across the rocks of the undermass. The long period of erosion needed to form this peneplain implies crustal stability during this time. The sequence of Tertiary rocks from coal-measures at the base, to marine limestones, to coal-measures and gravels at the top, indicates a complete cycle of sedimentation brought about by depression of the area beneath the sea, followed by uplift and return to land conditions. In view of the small variation in the total thickness of the marine Tertiary beds over the area mapped it can be concluded that, during the period of subsidence and earlier stages of uplift, the movements were epeirogenic rather than orogenic. The presence of such structures as Cannington Syncline and Craigmore Anticline indicate that shortly after the marine sediments emerged from the sea to become land the earlier regional epeirogenic movements changed to more local orogenic movements (the "Kaikoura" Orogeny of Cotton, 1916).

As the marine sediments rose from beneath the sea, sediments eroded from the first emergent portions are likely to have been deposited on the more slowly rising land around (see Fig. 2(b)). Such seems to be the origin of the Cannington Gravels. It is probable that the gravels, silts, and sands comprising this formation were eroded from the earlier emergent land which lay to the west of the Pareora District. The absence in these beds of fragments of Tertiary rocks is readily explained by the fact that, with the exception of the Craigmore Limestone and the various concretionary bands, the bulk of the sediments consists of unconsolidated sands and silts and other easily erodable beds. In the Pareora district the Cannington Gravels are non-marine, but farther east they are likely to have been deposited in a marine environment, as have the gravels at Makikihi (Collins, 1953).

As the Kaikoura movements continued, irregularities of the relief produced by differential uplift to the east of the Hunters Hills were probably smoothed out as rapidly as they formed, by aggradation of gravels derived from the erosion of the highland to the west. Finally a stage was reached during which there was an extensive piedmont alluvial fan or series of coalescing fans, similar to the Canterbury Plains but occupying a much higher elevation, extending from high up the Hunters Hills over the top of Mt. Misery block and Craigmore Anticline to the sea (see Fig. 2(b), stages 2 and 3). As the Hunters Hills and the blocks to the west continued to rise tectonically, this fan surface was built up by aggradation. Due to this aggradation and also to a slowing up of earth movements towards the close of the Kaikoura Orogeny, the earliest deposited Cannington Gravels, at any one place, were folded to a greater degree than those deposited later, and movement on the folds and faults probably had ceased by the time the uppermost gravels were deposited. Over the structural lows, such as Cannington Syncline, the gravels were possibly thousands of feet thick, but over the structural highs, such as Mt. Misery block and Craigmore Anticline, they were very thin or possibly absent in a few places. Moreover, numerous disconformities are to be expected over the structural highs (at times when the rate of uplift exceeded the rate of aggradation of Cannington Gravels) and in many places perhaps only the uppermost layers of Cannington Gravels were deposited. A thin veneer of gravel across, or adjacent to a structural high is therefore more likely to represent a layer from the youngest than from the oldest Cannington beds (see Fig. 2(b), stage 3). Where now exposed, the gravels overlie an eroded surface of either White Rock Coal-measures or Southburn Sand, but over structural highs they could have accumulated on older Tertiary formations or even directly on the undermass. This disconformity or angular unconformity between the Cannington Gravels and the beds beneath increases in magnitude towards the source area and structural highs, but probably decreases to vanishing point where the gravels are marine (see Fig. 2(b)). The field observation that the lower part of the Cannington Gravels consists mostly of silts, sand, and fine gravels, and the upper part of coarse gravels, can be related to the amount of relief in the source areas. During the initial stages of the Kaikoura Orogeny relief would be relatively small, and predominantly fine sediments would be produced. But as the movements intensified, relief increased, with the consequent production of coarse materials.

The presence near the base of the Cannington Gravels of silt beds up to 50 ft thick containing plant impressions suggests that at several times in the early history of the Mt. Misery block, uplift may have been so rapid that aggradation in the Cannington basin was arrested, and temporary ponding occurred. With the cessation or slowing up of the Kaikoura movements a long period of degradation has ensued and has finally produced the present landscape. During this period of degradation there may have been intervals of aggradation, due to climatic changes or minor earth movement, and Cannington basin may thus have been partly filled and excavated several times. But the net result has been degradation, which, guided largely by the buried structure as it became exposed, has resulted in the present topography. In the early stages of this period of degradation before the excavation of Cannington Basin had begun, basalt was erupted to form a sheet which now extends from Mt. Horrible to the sea. It seems probable that degradation had been in progress for some time prior to the eruption of the basalt, since at the point below the north trig. on Mt. Horrible only a few feet of Cannington Gravels are present beneath the silt under the basalt, and farther to the north the silt beneath the basalt directly overlies Southburn Sand.

GEOMORPHOLOGY

The effect of the deposition of the Cannington Gravels was to bury structures as they were formed. The effect of post-Tertiary erosion has been to re-expose structures so that the present landscape shows very close adjustment to the underlying structure. It is probable that most faults in the area were still active during the deposition of the Cannington Gravels, and that the fault scarps were progressively buried by these beds, thereby becoming "fossil" features. Post-Tertiary erosion has subsequently exhumed these "fossil" fault scarps.

Five features of the landscape require special mention. These are:

(1) The exhumed fossil peneplain on the back slopes of Mt. Misery block and Mt. Nessing fault splinters, which is probably part of the extensive pre-Tertiary peneplain.

(2) The slump topography developed on the silts and clays of the Cannington Gravels in the Motukaika Valley, and in the branches of the Little Pareora River west of Maungati. Similar topography is developed also on the Little Pareora Silt on the north side of the Little Pareora Valley (see Fig. 8), and on the west side of the Lower Pareora Gorge.

(3) The numerous sinkholes on the surface of the Craigmore Limestone where it forms the crest and eastern limb of Craigmore Anticline (see Fig. 8). Many of these sinkholes form aligned groups, which join with discordant junctions the headward ends of surface streams drainin gthe area. Other groups of sinkholes form "blind" valleys, not yet in surface connection (but probably connected underground) with surface stream valleys.

(4) Interfluves in Cannington basin eroded in both Maungati and Cannington Gravels, which have asymmetrical cross-profiles, apparently unrelated to the underlying structure (see Fig. 9). In profile the back slopes of the ridges are inclined at about 5 to 10°. It is suggested that these features are possibly related to climatic effects. In all cases the ridges trend in an easterly direction and the scarp slope invariably faces south, which is the shady side. Furthermore, where these ridges are followed back to the headward ends of the streams between them, it is found that the streams have symmetrical V-shaped valleys which become asymmetrical downstream, in some cases within a few hundred yards of the valley head. An alternative explanation, that the asymmetrical interfluves are due to recent tilting to the north, does not seem likely in view of the general accordance of summit level of the crests of the interfluves.

(5) The anomalous position of the Little Pareora River in a longitudinal valley near and parallel to the crest of Craigmore anticline suggests superposition from the Cannington Gravel surface of aggradation.

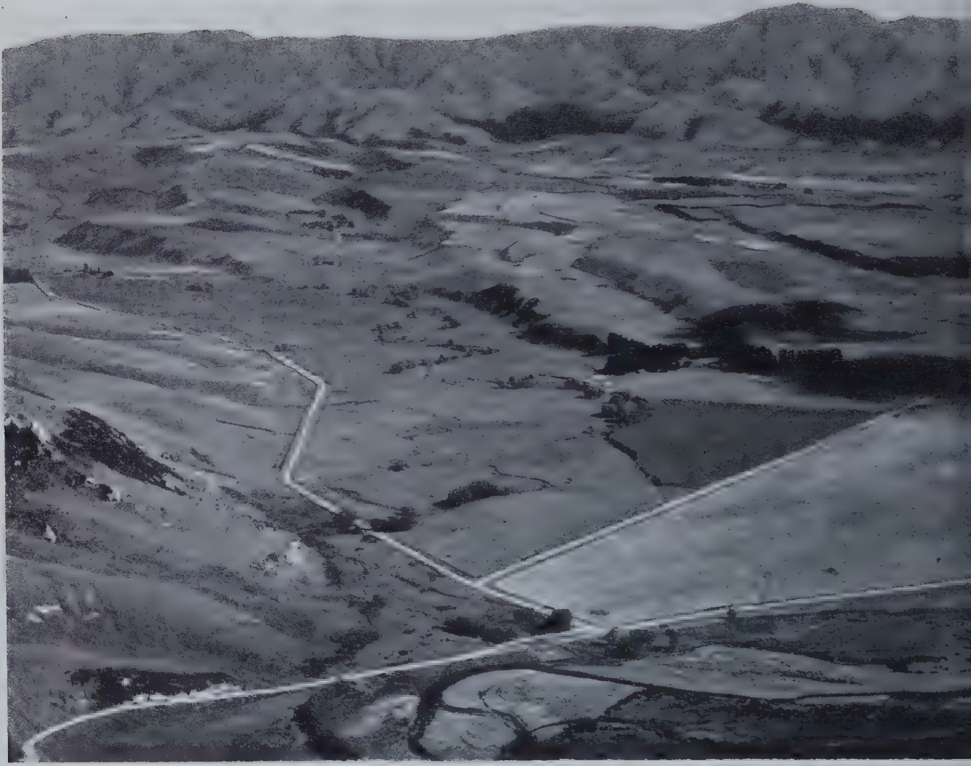


FIG. 9.—Asymmetrical interfluves eroded in Cannington and Maungati Gravels, Cannington basin. Hunters Hills with Mt. Nimrod (the highest peak in the photo) in the background; upstream end of the Lower Pareora Gorge in the foreground lower left. The Craigmore Limestone forming the steeply dipping north-west limb of Craigmore Anticline is in the middle left of the photo. (Photo reproduced by permission of V. C. Browne.)

FOSSIL LOCALITIES

Otaio Gorge

Downstream of Colliers Bush is exposed an interrupted sequence from Colliers Coal-measures to the Craigmore Limestone. The contact with greywacke is not exposed. Isolated slabs (not in place) of richly fossiliferous pebbly (quartz pebbles) Otaio Gorge Sandstone lie in the bed of the river about 200 yards downstream from the road bridge.

Dr J. Marwick (pers. comm., 31 March, 1949) noted a scarcity of Bortonian species, and, on the general appearance of the faunule was inclined at that time to correlate it with the ?upper Dannevirke series.

The following fossils were obtained from this conglomerate:

Baryspira n.sp.
Crassatellites australis (Hutton)
Crassatellites sp.

Cucullaea cf. *waihaoensis* Allan
Eoturris n.sp.
Hedecardium cf. *brunneri* (Hector)
Insolentia n.sp.
Longimactra n.sp.
?*Magnatica* sp.
Monalaria n.sp.
Notocallista (*Fossacallista*) *hectori* Finlay and Marwick
Notoplejona sp.
Paphirus n.sp.
Polinices (*Polinista*) n.sp.
Spirocolpus n.sp.
Struthiolarella sp.
Venericardia n.sp.
Zeacolpus n.sp.

Bluecliffs and Southburn Road Cutting

In this locality is exposed almost the whole thickness of the Bluecliffs Silt, but not its contact with the Graigmore Limestone. This is the type locality for the Otaian stage of Finlay and Marwick (1947). The following is a list of characteristic (i.e. most common) fossils from this type locality:

Alcithoe n.sp.
Austrofusus (*Neocola*) *apudalpha* Finlay
Austromitra n.sp.
Austrotoma lawsi Powell
Austrotoma nervosa Powell
Baryspira aff. *novaezelandiae* (Sowerby)
Baryspira robusta Marwick
Bathytoma haasti (Hutton)
Cirsotrema lyratum (Zittel)
Cominula (*Procominula*) *pulchra* (Suter)
Comitas fusiformis (Hutton)
Comitas n.sp.
Cucullaea australis Hutton
Dentalium solidum Hutton
Friginatica vaughani (Marwick)
Globisinum miocenicum (Suter)
Hima (*Mirua*) n.sp.
Inquisitor awamoaensis (Hutton)
Lentipecten hochstetteri (Zittel)
Lima cf. *paleata* Hutton
Limopsis zealandica Hutton
Marginella conica Harris
Neoguraleus (*Fusiguraleus*) aff. *flexicostata* Powell
Notacirsa elata (Suter)
Notocorbula pumila (Hutton)
Penion finlayi (Laws)
Poirieria primigena Finlay
Spinomelon evelynae Laws
Spinomelon mira Marwick
Spissatella trailli (Hutton)
Tanea socius (Finlay)
Typhis (*Typhinellus*) *hebetatus* Hutton
Uberella acerva Laws
Uberella n.sp. aff. *acerva* Laws
Vexithara nodosolirata (Suter)
Xymenella aff. *lepida* (Suter)
Zeacuminia biplex (Hutton)
Zexilia dalli (Suter)

Just opposite Drinnan's bridge, in the left bank terrace, the Bluecliffs Silt passes into the Southburn Sand. The transition is first a colour change; the change in texture does not occur until higher up in the sequence. Samples for foraminiferal study were taken above and below this colour change (F 11432, F 11433, F 11434)* to see if it was related to the Otaian-Hutchinsonian boundary but the samples indicated an age not older than Hutchinsonian. The fauna was similar to that obtained from the fossiliferous horizons of the Southburn Sand at White Rock River and at the fault contact of the Cannington Gravels with Colliers Coal-measures at Maungati. *Notorotalia spinosa* (Chapman) is common and *Virgulinopsis pustulata* Finlay is present.

The Otaian Stage as defined by Finlay and Marwick (1947) is said to extend up to the brown "sandstone" in the upper sands at Southburn (below Bluecliffs). Judged by the above, the upper limit of the Otaian would appear to lie in the blue silts .

The Southburn Sand crops out in many places from the Southburn road cutting to Higginbotham Road, the dip gradually decreasing from 7° to 3°. A unique feature of the sands and sandstones here is the presence of tubes about 1 to 2 cm in length and 1 mm in diameter. Their first appearance is approximately a hundred and fifty feet above the colour change, their last in the uppermost exposed horizon of the Southburn Sand, which is very near the top. Between these two levels they may be found in practically all outcrops. Although they occur in both sands and sandstones they are more common in the latter. Here they are found crammed in great abundance in thin sandstone slabs (up to six inches thick) to the exclusion of other fossils. They lie in the horizontal plane and are orientated in a north-east direction. A fragment of this sandstone was sent to Dr J. Marwick and the late Dr H. J. Finlay for examination. The fossil is either *Cadulus* (mollusc) or *Ditrupa* (worm-tube).

On molluscan evidence Dr J. Marwick places the upper horizon of these sands as Hutchinsonian or Awamoan. The following Mollusca were obtained from the uppermost horizon of the sands:

Cadulus n.sp.
Hima cf. *socialis* (Hutton)
Insolentia cf. *pareoraensis* (Suter)

On foraminiferal evidence (F 11435) the upper horizon of the sands here may be Awamoan. The late Dr H. J. Finlay stated (pers. comm., 19/3/49), "*Notorotalia spinosa* common, not many other foraminifera. Yet the fauna looks somewhat like a poorish one from Pukeuri, and I have a strong impression that it may be Awamoan, though no species to prove it could be found."

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*These F numbers refer to foraminiferal slides held at the New Zealand Geological Survey, Lower Hutt.

D. Squire's Farm

There is an interrupted sequence here from the Little Pareora Silt to the Southburn Sand. The former crops out in the hill facing the back road of the Hunters Hills where it dips at about 27° to the east. Near the base of the exposure, layers of simple corals (*Balanophyllia hectori* Tenison-Woods) occur, and beneath this horizon rounded quartz pebbles from Colliers Coal-measures are present in an earth flow.

The following details are from Dr Finlay's reports on foraminiferal samples collected from the limestone cliffs to the east of the homestead.

The Holme Station Limestone was found to be definitely of Whaingaroan age. A good fauna (F 11419) including:

Gaudryina reussi Stache
Rotaliatina sulcigera (Stache)
Uvigerina maynei Chapman
Vaginulinopsis cristellata (Stache)
Vaginulinopsis hochstetteri (Stache)

was obtained.

From Squires Greensand (F 11420), a fair fauna including

Lingulina cf. *bartrumi* Chapman
Notorotalia spinosa Chapman var.
Vaginulinopsis n.sp.

indicated definitely a Duntroonian age. A sample was taken from an almost pure glauconite sand to see if any facies fauna changes occurred. No fauna was obtained and the glauconite was reported as being very worn.

The Craigmore Limestone contained a Waitakian fauna (F 11421, F 11422, F 11423). In the upper part of this stone were many Ostracods, and in samples from the upper 20 ft in the outcrop in the left bank of the river the following are present (F 11424 to F 11431).

Anomalinoides miosuturalis (Finlay)
Discopulvinulina turgidus (Finlay)
Haeuslerella hectori (Finlay)
Notorotalia aff. *serrata* (Finlay)
Notorotalia cf. *spinosa* (Chapman)
Quinqueloculina n.sp
Siphogenerina aff. *striatissima* (Stache)

Lower Gorge of the Pareora River

The Otaio Gorge Sandstone is exposed in the side of the road through the gorge. It appears to be thicker than usual, and is for the most part unfossiliferous. The concretionary sandstone layers and quartz pebble conglomerates are not exposed. From the proximity of these sands to the greywacke it can be inferred that Colliers Coal-measures is either very thin or not present here.

There are no exposures at the upper end of the gorge, but at the lower end are interrupted exposures from the Otaio Gorge Sandstone to the Southburn Sand at Holme station.

Little Pareora River

This river has entrenched itself near the base of the Little Pareora Silt, which is exposed at several places along its bed from Maungati to its junction with the Pareora River. Near the junction with the Pareora a middle to upper horizon of the silt is exposed, but upstream lower horizons crop out until at Maungati the Otaio Gorge Sandstone is exposed about 200 yards below the junction of the north and south branches of the Little Pareora River. In the river-bed just above Elworthy's bridge the writer found a single fossil crab.

Maungati

The following Mollusca and Foraminifera (F 11417) indicative of a Hutchinsonian age were obtained from the Southburn Sand underlying the Cannington Gravels near the fault contact.

MOLLUSCA
Angulus sp.
Glycymeris sp.
Lentipecten sp.
Maorimactra sp.
Nucula cf. *sagittata* Suter
Zenatia

FORAMINIFERA
Notorotalia spinosa (Chapman)
Virgulopsis pustulata (Finlay)

Motukaika River

This locality is of interest stratigraphically as well as structurally in that Squires Greensand contains a distinct facies fauna. The best exposure of the greensand occurs in the second fault contact below Green's farm. The greensand differs from the usual in that it is considerably thicker (at least 30 ft), is very uniform in glauconitic content, and contains numerous small rounded pebbles of quartz and soft brown argillite, both commonly $\frac{3}{8}$ in. across. As well as the usual brachiopods, which are here very rare, the fauna contains (F 11418) *Notocallista*, *Dentalium*, Turridae and Naticidae, and the corals *Flabellum paroninum circulare* Tenison-Woods and *Notocyathus pedicallatus* Tenison-Woods. A sample of the greensand was sent to Dr Finlay who stated (pers. comm., 19/3/49), "Quite a fair fauna, not older than Duntroonian, but I cannot find anything that really limits it to this age and it could be a little younger, perhaps Waitakian".

White Rock River

The following is a list of macrofossils from the Southburn Sand where it is exposed in the left bank of the White Rock River about 30 yards upstream of the first bridge.

Acteon ovalis (Hutton)
Anomia trigonopsis (Hutton)
Austrofusus (*Zealandiella*) *subnodosa* (Hutton)
Austrotoma cf. *excavata* (Suter)
Austrotoma minor Finlay
Baryspira (*Alocospira*) *hebera* (Hutton)

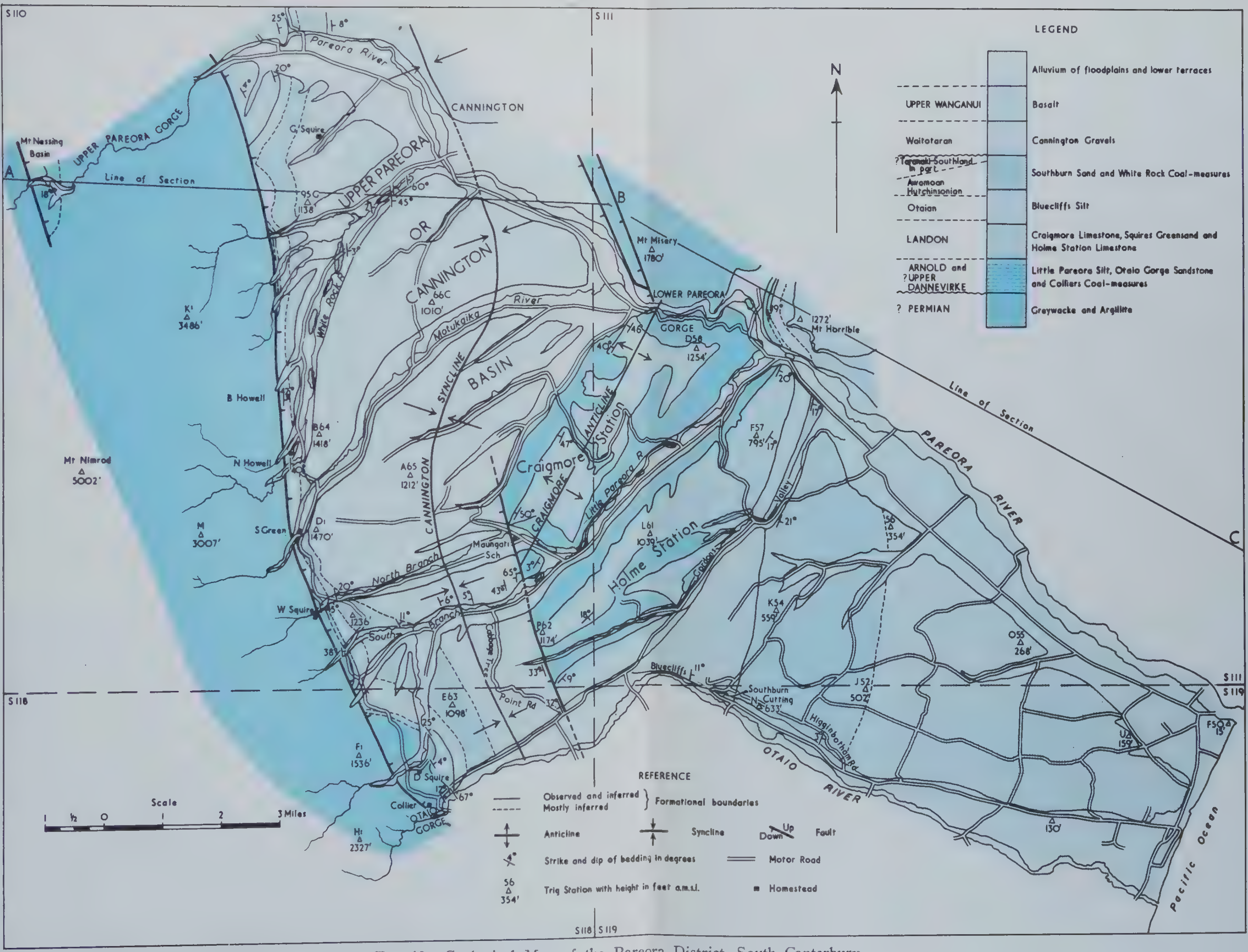

FIG. 10.—Geological Map of the Pareora District, South Canterbury.

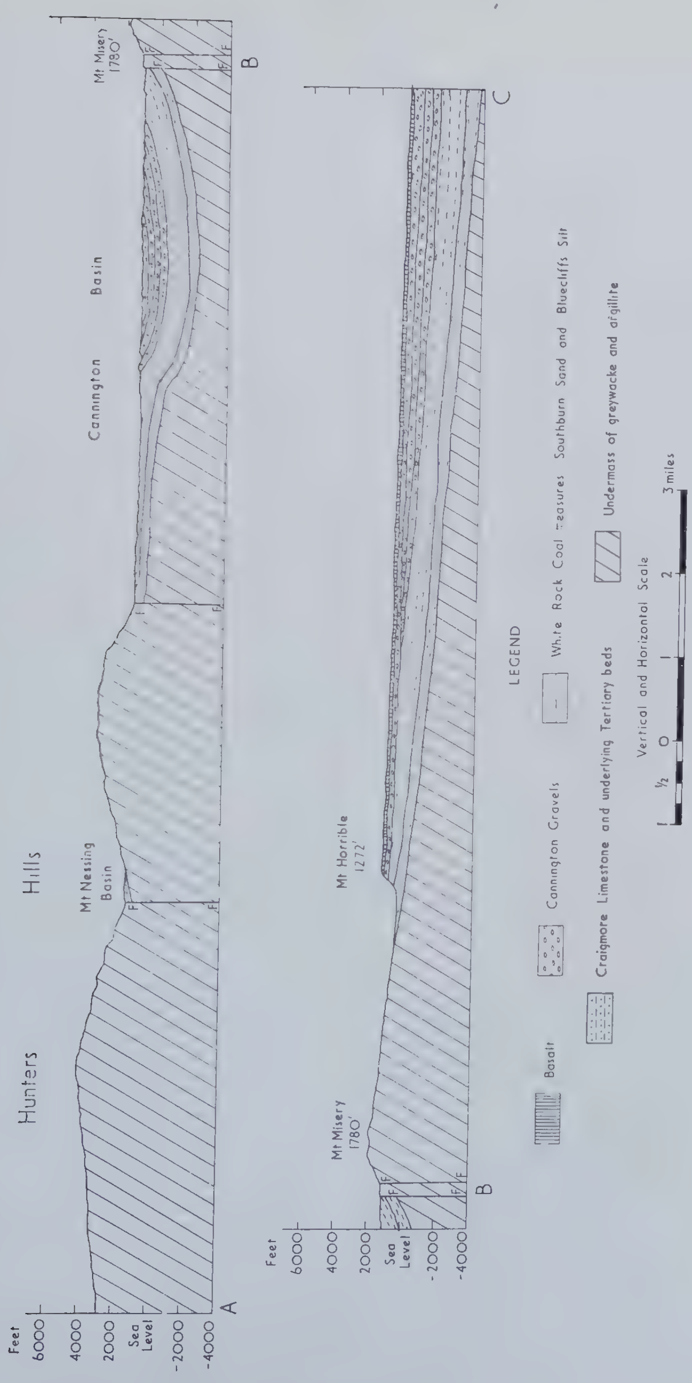
Hunters Hills
Mt Nessing Basin
Cannington Basin
Mt Misery 1780'
A
B
C
F
Feet
6000
4000
2000
Sea Level
-2000
-4000
Mt Horrible 1272'
LEGEND
Basalt
Cannington Gravels
White Rock Coal Measures Southburn Sand and Bluecliffs Silt
Craigmore Limestone and underlying Tertiary beds
Undermass of greywacke and argillite
Vertical and Horizontal Scale
1
½
0
1
2
3 miles

FIG. 11.—Geological cross-section.

Batillona n.sp.
Cirsotrema n.sp.
Conospirus huttoni (Tate)
Dentalium aff. *nanum* Hutton
Dentalium solidum Hutton
Dosinia sp.
Glycymeris (*Glycymerita*) *huttoni* (Marwick)
Hima (*Mirua*) *socialis* (Hutton)
Limopsis zitteli Ihering
Neoguraleus (*Fusiguraleus*) *leptosomus* (Hutton)
Notocorbula pumila (Hutton)
Parcora striolata (Hutton)
Penion marwicki (Finlay)
Polinices huttoni Ihering
Pteromyrtea laminata (Hutton)
Scalpomactra continua Finlay
Strombiformis aoteaensis (Marshall & Murdoch)
Struthiolaria (*Callusaria*) *spinosa* Hector
Tanea sublata Marwick
Tomopleura excavata (Hutton)
Turbonilla speighti Laws
Zeacolpus (*Tropicolpus*) *albolapis* (Finlay)
Zeacuminia pareoraensis (Suter)

Dr Marwick (pers. comm., 31/3/49) correlated the White Rock River fauna with the Awamoan and suggested that some points of difference are probably the result of different station.

Dr Finlay reported a small microfauna in a sample from near the top of the highest shell-bed (F 11415), in which *Notorotalia spinosa* (Chapman) is common and *Virgulopsis pustulata* (Finlay) is present. He considers the fauna to be no older than Hutchinsonian but it may be younger. The fauna was too small to give a definite decision.

Dr R. A. Couper reported as follows on samples of carbonaceous sand and sandy lignite from the White Rock Coal-measures in the White Rock River section: "Only sample S110/521 (L 1176) yielded a workable flora. Among the species identified, *Tricolpites mataurаensis* Couper, *Liliacidites intermedius* Couper, and an undescribed new coniferous species all make their last appearance in Southland Series floras. Other key species in the sample indicate a Pareora to Taranaki age. Available evidence suggests a Southland age for the sample. Besides the fossil spores and pollen grains numerous specimens of microplankton (mainly hystrichosphaerids) are also present, clearly indicating a marine of estuarine environment for the sample.

Sample S110/520 (L 1175) yielded only a poor preparation (including hystrichosphaerids) and no estimate of age could be made. Sample S 110/523 (L 1177) gave no flora."

Mt. Nessing Basin

All the beds up to the limestones are exposed in this basin and every formation other than the Craigmore Limestone and Squires Greensand is represented here by a facies differing to a varying degree from its correlative to the east of the Hunters. Another difference is the considerable development of Squires Greensand which is at least 100 ft thick. Only those beds below the Craigmore Limestone remain in the portion of the basin to the south of the Pareora River. There the whole sequence consists mostly of marine sands of varying colour underlain in two places by thin lignites and clays.

The following divisions can be made:

		Age
(e) Rust-yellow sands:	10 ft	
(d) Green-blue glauconitic silts:	25 ft	Whaingaroan
(c) Yellow-white sands, poorly fossiliferous:	250 ft	
(b) Richly fossiliferous sands:	15 ft	Bortonian
(a) Clays, lignite seams, carbonaceous shales:	12 ft	
Total minimum thickness:	312 ft	

All the beds except those near the west fault (where the dip is 50° to 60°) dip to the west at about 18°. Beds (a) and (b) are exposed in two outcrops of somewhat different facies. The first outcrop is adjacent to the greywacke in the west side of the basin in the right bank of the southern branch of the Pareora. The succession here is:

(5) Grey-brown sand, fossiliferous (Mollusca):	6 in.	Top
(4) Lignite:	6 in.	
(3) Carbonaceous dark brown silts:	3 ft 6 in.	
(2) Lignite:	3 in.	
(1) Sulphur-yellow coloured sand, unconsolidated, sparsely fossiliferous (Mollusca):	10 ft	Bottom

Bed 5 passes up into the rust-yellow sands comprising division “c”.

The upper 5 in. of the sulphur-yellow coloured sand is fossiliferous but the fossils occur only as casts or moulds and the sand is so loose that it is impossible to collect a specimen for macrofossil study unless some means of “lithifying” the deposit is devised. Fragments of kaolinised greywacke and argillite up to 2 in. diameter occur in this sand and in Bed 5, the grey-brown sand. The fossils in the latter were so poorly preserved that no collection was made.

The second outcrop of beds (a) and (b) is in the right bank of the northern branch of the Pareora about mid-way across the basin. This is the best exposure of the lowest fossiliferous sands. The succession is from top to bottom:

(3) Grey-blue coarse sand, fossiliferous (Mollusca) and very iron-stained in parts:	10 ft	Top
(2) Blue sand, fossiliferous (Mollusca), intensely iron-stained in places, with small fragments of carbonaceous material:	1 ft	
(1) Blue micaceous silt with shaley layers (Mollusca):	4 ft	Bottom

Bed 3 passes up into the yellow-white sand comprising division "c".

The state of preservation of the fossils is exceedingly poor but Dr Marwick was able to place the age of these beds as probably Bortonian on the presence of the following Mollusca:

Baryspira sp.
Dosinia sp.
Glycymeris (*Glycymerita*) sp.
Hedecardium brunneri (Hector) or *waitakiense* (Suter)
Maoritellina sp.
Maoricrypta sp.
Maurea sp.
Pleuromeris sp.
Scalpomactra sp.
Spissatella (or *Crasatellites*) sp.
Venericardia cf. *acanthodes* Suter
Zeacolpus sp.

No foraminiferal faunas were obtained from these sands. About two hundred yards downstream from this outcrop white and yellow clays are exposed in the bed of the river and further down in the left bank partly kaolinised greywacke crops out.

Division "c", the yellow-white sands, is exposed in the cliff-faces to the north and south of the branches of the Pareora. Sands in the south are more mottled with iron-staining, but fossils are more easily found. The fossils are mostly casts and moulds so poorly preserved that all that their presence demonstrates is that these sands are marine.

Near the top of the "badland" gully at the western extremity of this cliff-face these sands pass up into green-blue glauconitic silts comprising division "d". Four subdivisions of these beds can be made:

(4) Blue silt, slightly glauconitic:	7 ft	Top
(3) Dark blue-green glauconitic silt:	4 ft	
(2) Green glauconitic silt:	4 ft	
(1) Brown glauconitic silt:	4 ft	Bottom

Foraminiferal samples were taken from each of these beds but all proved negative save Bed 4, in which a good fauna was obtained, which proved a definite Whaingaroan Age (F 11416). This fauna included:

Cibicides thiara Stache
Eggerella aff. *ihungia* Finlay
Gaudryina reussi (Stache)
Guttulina regina (Brady, Parker, and Jones)
Gyroidinoides
Gyroidina aff. *allani* (Finlay)
Marginulinopsis cf. *interruptus* (Stache)
Rotaliatina sulcigera (Stache)

Thus this blue silt is the correlative of the Holme Station Limestone to the east of the Hunters Hills.

Some miles north of the Pareora River the calcareous greensands and limestone crop out just north of Rocky Gully and in the Opawa River. In both these places the greensands are at least 100 ft thick, and they pass up into the typical Craigmore Limestone, which is faulted against greywacke.

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SEA-LEVEL RECORDINGS AT SCOTT BASE, ANTARCTICA, 1957

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(Received for publication, 2 March 1958)

Summary

Sea-level recordings have been made at Scott Base in McMurdo Sound with a modified Foxboro liquid level recorder, intermittently from March to July 1957, and continuously throughout December 1957. Because of the difficulty of operating such equipment under Antarctic conditions, the sites and methods of installation are here described in detail. Hourly values are tabulated, and the results for December 1957 presented graphically.

INTRODUCTION

As part of the New Zealand I.G.Y. programme a sea-level recorder was installed, in March 1957, at Scott Base (Lat. 77° 51′ 30″ S, Long. 166° 48′ E), Ross Island, Antarctica (Fig. 1). From Pram Point on

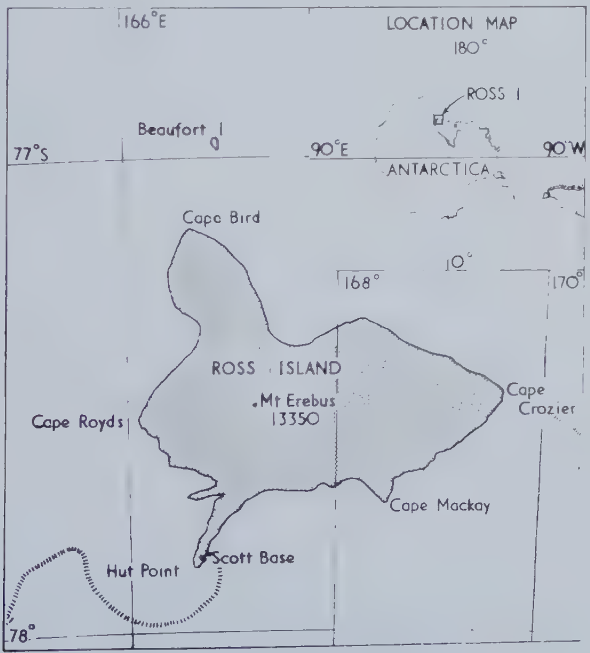

Fig. 1.—Locality map.

N.Z. J. Geol. Geophys. 2 : 297-314.

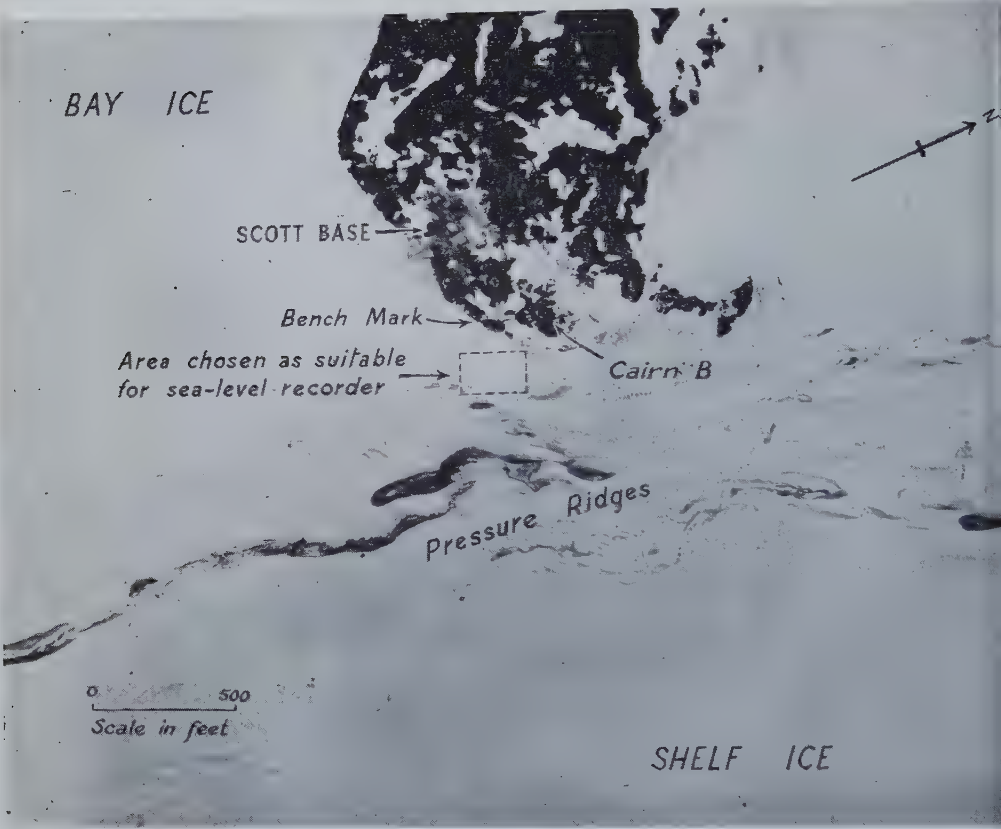

Fig. 2.—Aeral view of Pram Point.

the south of the Hut Point Peninsula a line of pressure ridges curving south-westwards separates the shelf ice from the bay ice. An area on the bay ice between Pram Point and the pressure ridges, about 500 ft from the Scott Base buildings, where the bottom shelves gradually from the exposed rock on the shore about 150 ft away and reaches a depth of 15 to 30 ft, was chosen as a suitable site (Fig. 2).

Instrument

The Foxboro liquid level recorder, designed to operate down to a depth of 20 ft, consisted of two parts. The underwater unit was a brass air-bell 5 in. in diameter and $2\frac{1}{2}$ in. deep, closed by a flexible cup-shaped neoprene diaphragm. This unit was connected to the pressure capsule in the recorder on the surface by a length of copper tube $\frac{1}{4}$ in.

in internal diameter. In the recorder unit on the surface the pressure capsule (similar to that in an aneroid barometer) drove, through a system of levers, a pen which recorded on a circular chart, 11 in. in diameter. The lever system was such that a change in water level of 1 ft moved the pen 0·2 in. The chart, which made one revolution per week, was driven by a Horstmann Gear Co. thermograph clock (Fig. 3). The clock was oiled with Vacuum Oil Co. instrument oil B3/TR/77.

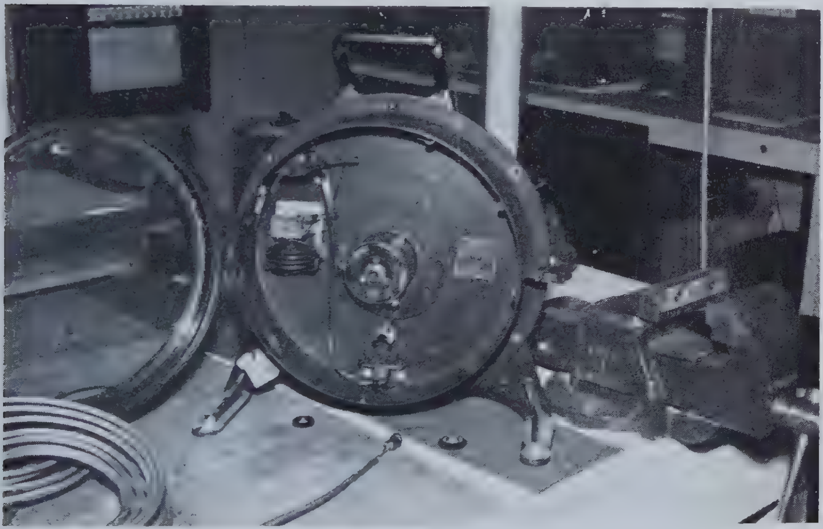

FIG. 3.—The recorder with chart plates removed.

INSTALLATION

During 1957 the sea-level recorder was moved to three different sites (Fig. 4).

Site 1

For convenience, site 1 was finally chosen near the pressure ridges where the bay ice was only a few feet thick, whereas a short distance away the thickness increased sharply to about 16 ft. A hole had been attempted in the thicker ice but had been abandoned when sea water was seeping into it faster than it could be removed. The hole through the ice was "cased" with a 44 gallon drum, with top and bottom removed, to facilitate keeping the hole free of ice.

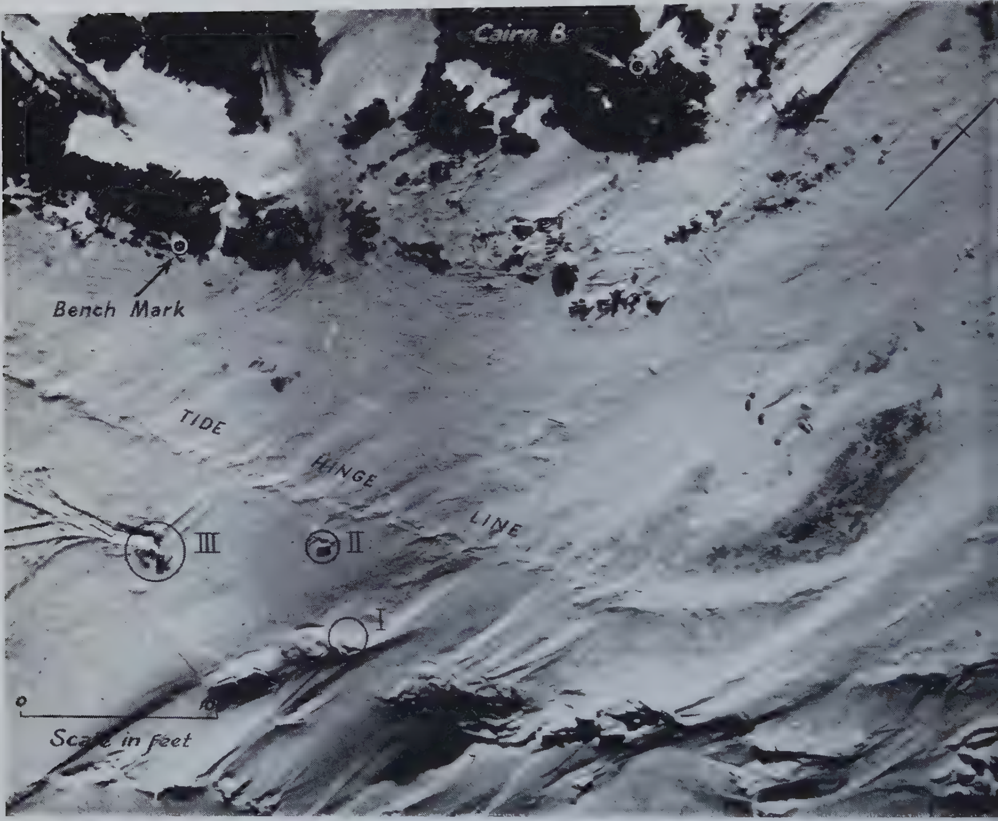

FIG. 4.—Tide gauge and bench mark sites.

The diaphragm unit was attached 5 ft from the bottom end of a 25 ft length of 2 in. diameter galvanized water pipe, the recorder being attached to the top. In the normal vertical position with the bottom end resting on the sea bed the recorder was about 5 ft above the ice surface and the underwater unit 15 ft below (Figs 5 and 8).

A kerosene heater was installed in the small hut built over the recorder to assist in keeping the hole free of ice so that the height of the diaphragm above the sea bed would remain constant. This was necessary because the bay ice moves up and down with the tide.

Before installation the diaphragm-recorder distance had been measured, thus enabling the calibration of the recorder to be checked by measuring the height of the recorder above the surface of the water. This was done frequently and the calibration was consistently found to be better than 0·1 ft.

Apart from clock stoppages, caused by low temperatures, this method worked well from 9 March until 13 April, when some fault in the heater set fire to the hut. Luckily the fire was put out before the recorder was irreparably damaged.

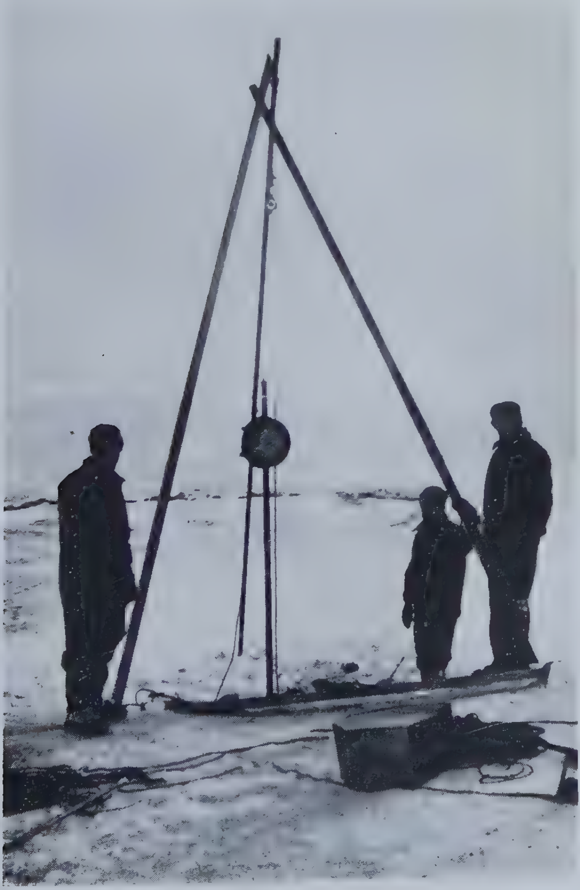

FIG. 5.—Site 1.

As the fire necessitated the removal and repair of the recorder, and the pressure ice was flattening the 44 gallon drum, a more suitable site was selected.

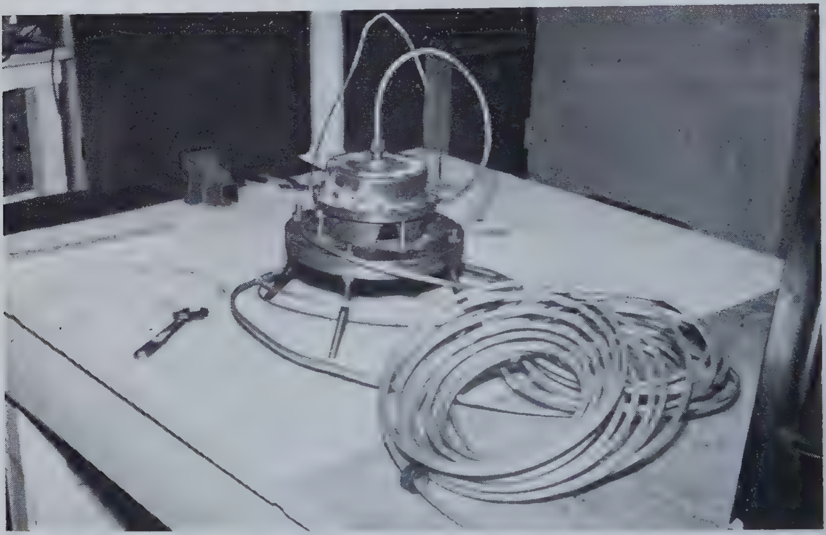

FIG. 6.—Underwater unit for Site 2.

Site 2

Site 2 (refer Fig. 4) was approximately 35 ft north-west of Site 1. No trouble was experienced with water seepage when digging the hole, possibly because the temperatures were much lower than when Site 1 was selected. At 9·5 ft the bottom of the ice was reached, the sea bed being 7 ft below the bottom of the ice.

From experience gained at Site 1 it was obvious that some system which did not require a hole to remain open was desirable. Therefore, the underwater unit was weighted and mounted on legs so that it would sit on the sea bottom, being connected to the recorder only by the $\frac{1}{4}$ in. copper tube which was bent into loose coils below the ice to allow for the rise and fall of the recorder (Fig. 6). Recording commenced on 30 April but, in spite of daily inspection (except during periods of blizzard) the clock was still stopping occasionally and some days of record were lost.

By 24 July the increase in the thickness of the ice, by freezing of the sea underneath and build-up of snow on the surface, was apparently sufficient to cause the ice to trap the underwater unit. As no spare underwater unit was available, no satisfactory recordings were obtained until a new unit was received from New Zealand late in November.

Site 3

By now it was evident that for the sea-level recorder to operate continuously at Scott Base the site chosen would have to meet rigid specifications.

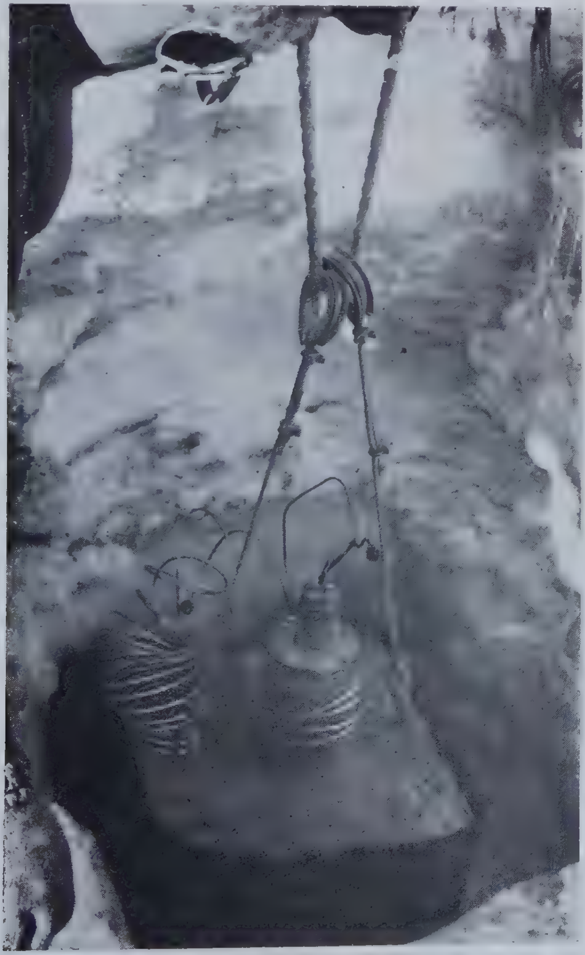

FIG. 7.—Lowering the underwater unit to the bottom at Site 3.

The recorder was built to operate in a maximum depth of 20 ft, though it was anticipated that this could be increased to 25 to 27 ft without damage to the pressure capsule. The winter ice thickness was about 15 to 18 ft and the highest tide recorded about 3·5 ft. These factors meant that it was desirable for the diaphragm unit to be as deep as the recorder's pressure capsule would allow. That is, a mean depth of 24 to 25 ft.

With the help of the engineers, a post-hole type borer was made from a cylindrical 5 gallon drum and several pieces of $\frac{3}{4}$ in. water pipe. Also, an ice chisel was made from a 5 in. × 9 in. piece of $\frac{5}{16}$ in. steel plate. The chisel was used to break the hard ice and the borer to remove the cuttings.

Two exploratory holes were drilled, one proving to have a water depth of 97 ft and the other 16 ft. To avoid the considerable amount of work involved in further unsuitable holes, use was made of the fact that Ross Island, being volcanic, is highly magnetic. Several short traverses with a Watts vertical magnetic balance were made and from the control provided by the depths at the two holes already drilled a suitable spot was selected, the depth later proving to be 25 ft (refer Fig. 4).

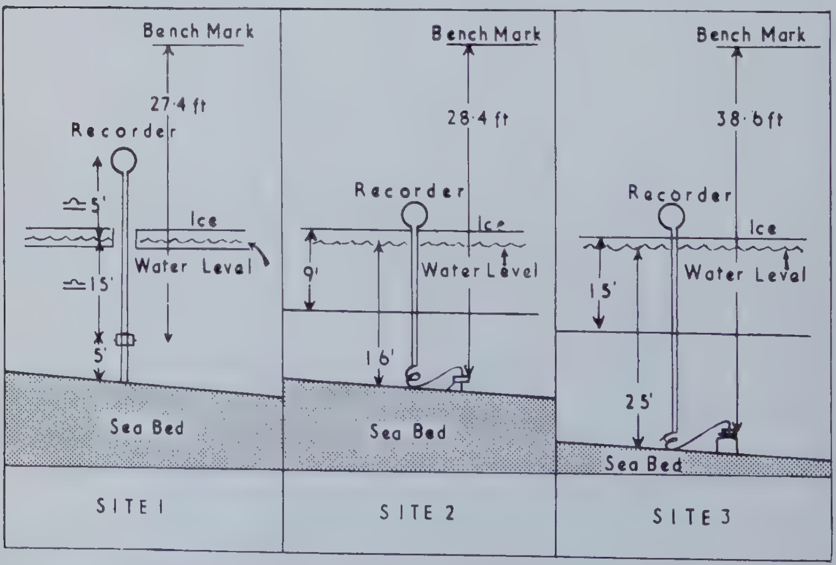

FIG. 8.—Diagrammatic representation of vertical sections at sites.

It was decided that the diaphragm unit should be mounted on a heavy concrete block so that it would sit firmly on the sea bed, and not be disturbed by seals or other marine life. This meant that a 3 ft square hole had to be dug through 5 ft of snow and a further 10 ft of ice. Working through 9 ft of water, the last foot of ice proved difficult to remove. The explosion from one pound of gelignite placed at the bottom of the hole blew the bottom out but caused a large volume, later estimated at 5 cubic yards, of "ice plates" to be formed. The "ice plates" varied in size between 9 in. × 6 in. and 2 in. × 2 in. by $\frac{1}{4}$ in. thick. They were characterized by two sets of parallel cracks at right-angles to each other. Some of the plates contained bottom fauna.

After clearing all the "ice plates" from the hole, the 20 in. × 20 in. × 10 in. concrete block with the diaphragm unit embedded, was lowered to the bottom with the aid of a tractor and block and tackle (Fig. 7). The recorder was enclosed in a large box on the surface of the ice. The sea-level recorder started recording again on 27 November 1957, and has been operating almost continuously since. (February 1959.)

RESULTS

Results are given in Table 1.

Levels at each site were taken with a Wild level and staff relative to a stainless steel bench mark fixed into a rock outcrop nearby (Fig. 2). A concrete block with a brass plate engraved "SEA LEVEL DATUM" was placed alongside the stainless steel pin.

At Sites 2 and 3 the levels of the diaphragm unit were found by using a measured length of cord (attached to the unit before lowering it), together with the level and staff.

The levels at the various sites are shown diagramatically in Fig. 8. However, for convenience, all results have been adjusted to the diaphragm unit depth at Site 3, i.e., 38·6 ft below the bench mark. Times are G.M.T. Because of clock troubles and slowness of movement (one revolution per week) times are probably correct only to ± 10 min. Heights are given in feet. The order of accuracy of reading is ± 0·1 ft.

The increased depth, 25 ft, at Site 3 caused the pen to go off scale. To bring it back, considerable adjustment had to be made to the pen linkage. A set of levels was taken to check the calibration. In Table 2 these levels are given.

SEA-LEVEL VALUES

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
9					27·0	27·4	27·5	27·6	27·5	27·3	27·0	26·6
10	25·8	26·0	26·2	26·6	26·9	27·1	27·3	27·4	27·3	27·2	27·0	26·5
11	25·2	25·5	25·7	26·0	26·4	26·6	26·9	27·0	27·1	27·0	26·9	26·5
12	24·7	24·9	25·2	25·5	25·9	26·2	26·5	26·8	27·0	27·1	27·1	26·9
13	24·9	25·0	25·2	25·5	25·9	26·2	26·6	26·8	27·0	27·1	27·2	27·0
14	24·8	24·7	24·8	25·0	25·3	25·6	25·9	26·2	26·3	26·4	26·4	26·4
15	25·0	24·9	24·8	24·9	25·0	25·4	25·6	25·9	26·0	26·1	26·1	26·0
16												
17	25·9	25·7	25·5	25·4	25·4	25·4	25·5	25·5	25·5	25·5	25·4	25·2
18						25·7	25·7	25·7	25·7	25·6	25·5	25·4
19	26·7	26·8	26·7	26·7	26·7	26·6	26·4	26·2	26·0	25·9	25·8	25·6
20	26·6	26·9										
21			26·6	26·7	26·8	26·7	26·6	26·4	26·1	25·9	25·6	25·4
22	25·6	26·0	26·3	26·7	27·0	27·1	27·2	27·1	26·9	26·7	26·4	26·1
23	25·7	26·0	26·4	26·7	27·1	27·4	27·6	27·6	27·4	27·1	26·7	26·4
24	25·5	25·7	26·0	26·4	26·7	27·0	27·3	27·4	27·3	27·2	27·0	26·6
25	25·4	25·5	25·6	25·9	26·2	26·7	27·0	27·2	27·3	27·2	27·1	26·7
26	25·9	26·0	26·1	26·4	26·8	27·2	27·3	27·3	27·3	27·2	27·1	26·9
27	25·8	25·7	25·7	25·7	25·8	26·1	26·4	26·7	26·8	26·8	26·7	26·7
28	25·7	25·6	25·4	25·4	25·4	25·5	25·8	26·0	26·1	26·2	26·2	26·1
29	25·7	25·5	25·3	25·2	25·2	25·2	25·4	25·6	25·8	25·9	25·9	26·0
30	25·9	25·8	25·7	25·6	25·5	25·5	25·6	25·6	25·7	25·7	25·7	25·6
31	26·1	26·0	25·9	25·8	25·7	25·6	25·6	25·5	25·5	25·4	25·4	25·4

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
1	26·2	26·2	26·1	26·0	25·9	25·8	25·6	25·5	25·2	25·1	25·0	24·9
2	26·0	26·0	26·0	25·9	25·8	25·7	25·5	25·2	25·1	24·9	24·7	24·5
3	26·3	26·4	26·5	26·5	26·5	26·4	26·1	26·0	25·7	25·3	25·1	24·8
4	26·3	26·5	26·6	26·6	26·7	26·7	26·6	26·4	26·1	25·7	25·5	25·1
5	26·4	26·6	26·8	26·9	27·0	27·1	27·0	26·9	26·6	26·2	25·8	25·4
6	26·2	26·5	26·6	26·8	27·0	27·1	27·1	27·0	26·8	26·5	26·1	25·7
7	26·3	26·7	26·9	27·1	27·3	27·5	27·6	27·6	27·5	27·2	26·8	26·3

FOR SCOTT BASE

Month: March Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
26·2	25·8	25·5	25·3	25·2	25·1	25·1	25·2	25·3	25·4	25·5	25·6
26·2	25·7	25·4	25·1	24·9	24·8	24·7	24·7	24·8	24·8	24·9	25·0
26·2	25·8	25·4	25·0	24·8	24·6	24·5	24·5	24·5	24·5	24·6	24·6
26·7	26·4	26·1	25·7	25·5	25·2	25·1	25·1	25·0	24·9	24·9	24·9
26·9	26·6	26·4	26·1	25·9	25·7	25·5	25·4	25·2	25·1	25·0	24·9
26·3	26·2	26·1	26·0	25·8	25·7	25·7	25·7	25·6	25·5	25·3	25·1
25·9	25·8	25·8	25·8	25·8	25·8	25·8	25·8				
						25·5	25·7	25·9	26·1	26·1	26·1
25·0	25·0	25·0	25·1								
25·2	25·1	25·0	25·0	25·0	25·1	25·3	25·6	25·8	26·2	26·4	26·7
25·5	25·2	25·1	25·0	25·0	25·1	25·1	25·2	25·4	25·7	26·1	26·4
25·2	25·0	24·9	24·8	24·8	24·7	24·7	24·7	24·7	24·8	25·0	25·3
25·8	25·5	25·4	25·4	25·4	25·4	25·4	25·3	25·3	25·3	25·4	25·6
26·1	25·8	25·6	25·5	25·4	25·4	25·4	25·3	25·3	25·3	25·3	25·4
26·2	26·0	25·7	25·6	25·5	25·5	25·5	25·5	25·5	25·4	25·3	25·3
26·5	26·2	25·9	25·8	25·6	25·6	25·6	25·7	25·7	25·8	25·9	25·9
26·6	26·5	26·3	26·2	26·2	26·2	26·1	26·2	26·2	26·1	26·0	25·9
26·3	26·2	26·1	26·0	26·0	25·9	25·9	26·0	25·9	25·9	26·0	25·9
25·9	25·8	25·7	25·7	25·7	25·6	25·7	25·7	25·7	25·8	25·8	25·8
26·0	25·9	25·9	25·8	25·8	25·8	25·7	25·8	25·9	25·9	26·0	26·0
25·6	25·5	25·5	25·5	25·5	25·6	25·7	25·8	25·9	26·0	26·1	26·2
25·4	25·4	25·4	25·5	25·6	25·6	25·7	25·9	26·0	26·1	26·2	26·2

Month: April Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
24·8	24·8	24·9	24·9	25·0	25·0	25·1	25·2	25·5	25·7	25·8	25·9
24·5	24·6	24·7	24·8						26·0	26·1	26·2
24·6	24·5	24·5	24·6	24·8	25·0	25·2			25·7	26·0	26·2
24·8	24·7	24·6	24·6	24·8	24·9	25·0	25·2	25·4	25·7	25·9	26·2
25·2	24·8	24·7	24·7	24·6	24·7	24·9	25·0	25·2	25·4	25·7	26·0
25·5	25·2	24·9	24·8	24·9	25·0	25·2	25·3	25·4	25·6	25·9	26·1
26·0	25·6	25·2	25·1	25·0	25·0	25·0					

Sea-level Values for

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
1			26·3	26·2	26·1	25·7	25·3	25·2	24·7	24·4	24·2	24·0
2	26·8	26·9	27·0	27·0	26·9	26·7	26·5	26·2	25·8	25·2	24·9	24·7
3	27·0	27·2	27·3	27·4	27·4	27·2	27·0	26·7	26·3	25·8	25·5	25·1
4	27·0	27·1	27·2	27·3	27·4	27·3	27·1	26·9	26·5	26·1	25·6	25·2
5	26·5	26·7	26·8	26·9	27·1	27·2	27·2	27·1	26·7	26·2	25·8	25·5
6	26·1	26·3	26·4	26·7	26·9	27·0	27·0	27·0	26·6	26·2	26·0	25·6
7	25·6	25·8	26·0	26·1	26·3	26·4	26·5	26·5	26·4	26·2	25·8	25·5
10	25·7	25·6	25·6	25·6	25·7	25·8	25·9	25·9	25·7	25·6	25·4	25·3
14												
15	28·3	28·2	28·1	27·7	27·4	27·2	26·6	26·2	25·7	25·3	25·0	24·8
16	28·1	28·1	27·7	27·5	27·2	26·8	26·4	26·0	25·6	25·2	24·9	24·7
17	27·6	27·5	27·4	27·2	27·0	26·7	26·2	25·7	25·3	25·1	24·8	24·7
18	27·4	27·5	27·5	27·4	27·2	27·1	26·6	26·2	25·9	25·7	25·4	25·2
19	27·0	27·2	27·3	26·9	26·9	26·8	26·6	26·2	26·0	25·6	25·4	25·2
20	26·6	26·7	26·8	26·9	26·9	26·8	26·6	26·2	26·0	25·6	25·4	25·2
21	25·8	25·9	26·0	26·1	26·2	26·4	26·4	26·2	26·0	25·7	25·3	25·1
24	25·5	25·2	25·1	25·0	25·0	25·1	25·1	25·1	25·0	24·8	24·6	
25	25·4	25·2	24·9	24·8	24·7	24·7	24·7	24·7	24·6	24·5	24·4	24·3
26	26·1	26·0	25·6	25·3	25·1	25·0	24·9	24·7	24·4	24·3	24·2	24·2
27	26·0	25·8	25·4	25·2	24·8							
28												
29	26·6	26·5	26·4	26·2	26·0	25·7	25·2	25·0	24·4	24·2	23·9	23·8
30	27·1	27·0	26·8	26·6	26·2	25·9	25·5	25·1	24·6	24·4	24·1	24·0
31	27·4	27·2	27·1	26·9	26·5	26·1	25·6	25·2	24·7	24·3	24·1	24·0

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
1	26·7	26·6	26·4	26·4	26·2	25·7	25·3	25·0	24·5	24·2	24·0	23·9
3	26·1	26·3	26·4	26·5	26·6	26·5	26·4	26·2	26·0	25·6	25·3	25·1
4	26·0	26·1	26·2	26·3	26·3	26·4	26·4	26·2	25·9	25·7	25·4	25·3
23												
24	27·3	27·2	26·9	26·5	26·2	25·9	25·7	25·6	25·4	25·3	25·2	25·0
25	27·8	27·6	27·2	26·8	26·4	26·1	25·9	25·6	25·3	25·1	24·9	24·7
26	27·6	27·5	27·1	26·7	26·4	26·1	25·7	25·4	25·0	24·7	24·5	24·4
27	28·0	27·8	27·6	27·2	27·0	26·6	26·3	25·9	25·5	25·1	24·9	24·7
28	27·9	27·8	27·6	27·3	27·0	26·6	26·2	25·8	25·3	24·8	24·5	24·2
29	27·1	27·2	27·1	27·0	26·7	26·5	26·2	25·7	25·4	25·0?	24·6?	24·2?
30	26·7	26·7	26·5	26·4	26·3	26·2	26·0	25·7	25·3	25·0	24·7	24·4

Scott Base—*Continued*

Month: May   Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
24·0	24·1	24·2	24·3	24·5	24·7	25·0	25·3	25·7	26·1	26·5	26·7
24·4	24·3	24·2	24·3	24·4	24·7	24·9	25·3	25·7	26·1	26·5	26·8
24·8	24·7	24·6	24·6	24·7	24·8	25·0	25·2	25·6	26·0	26·4	26·7
25·0	24·7	24·5	24·5	24·6	24·7	24·8	25·1	25·2	25·6	25·9	26·2
25·2	24·9	24·8	24·6	24·6	24·7	24·7	24·8	25·0	25·2	25·6	25·8
25·4	25·1	24·9	24·8	24·8	24·8	24·9	25·0	25·1	25·2	25·4	25·5
25·2	25·2	25·4	25·6	25·8	25·9	26·1	26·4	26·4	26·5	26·5	26·4
											28·2
24·7	24·7	24·7	24·8	24·9	25·2	25·4	26·0	26·5	27·2	27·7	28·0
24·6	24·6	24·6	24·7	24·9	25·2	25·5	26·0	26·5	27·0	27·3	27·5
24·7	24·8	24·9	24·9	25·0	25·2	25·4	25·7	26·3	26·7	27·0	27·2
25·2	25·2	25·2	25·2	25·4	25·5	25·6	25·9	26·2	26·5	26·7	26·9
25·2	25·2	25·3	25·4	25·4	25·5	25·6	25·7	26·0	26·2	26·4	26·5
25·2	25·2	25·2	25·2	25·2	25·2	25·2	25·3	25·4	25·5	25·6	25·7
25·0	24·9	24·9	25·0	25·0	25·1	25·2	25·3	25·4	25·5	25·6	25·6
24·3	24·4	24·6	24·9	25·1	25·3	25·5	25·7	25·9	26·1	26·2	26·2
24·2	24·2	24·4	24·5	24·7	25·0	25·2	25·4	25·7	25·9	26·0	26·1
											26·7
23·8	23·9	24·0	24·2	24·4	24·8	25·2	25·8	26·2	26·5	26·9	27·1
24·0	24·1	24·4	24·6	24·9	25·3	25·7	26·2	26·7	27·0	27·3	27·4
23·9	24·0	24·1	24·2	24·5	24·9	25·3	25·8	26·3	26·5	26·7	26·7

Month: June   Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
23·7	23·8	23·9	24·1	24·2	24·6	25·1	25·4				
24·8	24·7	24·7	24·7	24·7	24·7	24·8	24·8	25·0	25·2	25·5	25·8
25·0	24·9										
											27·3
24·9	25·0	25·2	25·4	25·7	26·1	26·4	26·7	27·1	27·4	27·7	27·9
24·7	24·8	25·0	25·3	25·7	26·0	26·3	26·7	27·1	27·4	27·7	27·7
24·4	24·5	24·7	25·1	25·3	25·8	26·2	26·7	27·2	27·5	27·8	28·0
24·6	24·6	24·8	25·0	25·2	25·7	26·1	26·5	26·9	27·3	27·6	27·9
24·1	24·0	24·0	24·2	24·4	24·6	24·8	25·2	25·7	26·2	26·7	27·0
24·0?	23·9?	23·9?	24·0?	24·1?	24·2?	24·4?	24·7?	25·2?	25·8?	26·2?	26·6
24·2	24·0	23·9	23·9	24·1	24·2	24·4	24·8	25·2			26·2

Sea-level Values for

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
1	26·4	26·4	26·5	26·5	26·4	26·3	26·2	26·0	25·7	25·5	25·2	25·1
2	26·3	26·4	26·5	26·5	26·4	26·4	26·3	26·2	26·0	25·7	25·4	25·3
3	26·0	26·0	26·0	25·9	25·8	25·7	25·7	25·6	25·4	25·2	25·0	25·0
4	25·7	25·7	25·6	25·6	25·4	25·4	25·3	25·2	25·1	24·9	24·8	24·8
5	25·8	25·7	25·7	25·5	25·5	25·5	25·4	25·2	25·1	25·0	24·8	24·8
6	26·1	25·8	25·5	25·4	25·2	25·2	25·0	24·9	24·7	24·6	24·4	24·4
7	26·1	25·7	25·5	25·2	25·0	24·9	24·8	24·7	24·4	24·2	24·1	24·1
8	26·2	25·7	25·4	25·2	25·0	24·8	24·6	24·3	24·2	24·0	24·0	24·0
13	27·4	27·4	27·3	27·1	27·0	26·8	26·5	26·3	26·1	25·8	25·6	25·5
14	27·1	27·2	27·2	27·1	26·9	26·8	26·6	26·3	26·0	25·7	25·6	25·4
15	26·9	27·0	27·0	26·9	26·9	26·7	26·7	26·5	26·1	25·9	25·6	25·4
16	26·4	26·5	26·5	26·4	26·4	26·4	26·3	26·1	25·8	25·5	25·4	25·3
17	26·2	26·2	26·2	26·2	26·3	26·3	26·3	26·2	26·0	25·7	25·6	25·5
18	26·0	25·9	25·9	25·9	25·9	25·9	25·9	25·8	25·7	25·5	25·3	25·3
19	26·0	25·8	25·7	25·6	25·6	25·7	25·8	25·8	25·7	25·5	25·4	25·4
20		26·4	26·2	25·9	25·7	25·7	25·7	25·8	25·8	25·7	25·5	25·4
21	26·7	26·4	26·2	25·9	25·8	25·7	25·7	25·8	25·8	25·7	25·7	25·5
22	27·3	27·0	26·4	26·1	25·9	25·6	25·6	25·6	25·4	25·3	25·2	25·2
23	27·6	27·2	26·6	26·2	25·8	25·6	25·4	25·4	25·2	25·1	25·1	25·0

Station: C.S.A.G.I. A991

Reading (in feet) on the hour (G.M.T.)

day	1	2	3	4	5	6	7	8	9	10	11	12
1	24·7	24·6	24·8	24·9	25·0	25·3	25·6	25·8	26·0	26·1	26·2	26·0
2	24·5	24·5	24·7	24·8	24·9	25·1	25·4	25·7	25·9	26·1	26·2	26·0
3	24·2	24·4	24·5	24·6	24·9	25·1	25·5	25·8	26·2	26·4	26·5	26·3
4	24·5	24·6	24·8	25·0	25·2	25·6	26·0	26·4	26·7	26·9	27·1	26·9
5	24·2	24·5	24·6	24·8	25·1	25·4	25·8	26·2	26·7	26·9	27·2	27·3
6	24·2	24·4	24·6	24·9	25·2	25·7	26·2	26·6	26·8	26·9	27·0	26·8
7	23·7	23·8	23·9	24·2	24·5	24·9	25·4	25·8	26·3	26·6	26·9	27·0
8	23·5	23·7	23·9	24·1	24·3	24·6	25·1	25·5	26·1	26·5	26·9	27·2
9	23·7	23·6	23·5	23·7	23·8	24·1	24·4	24·7	25·2	25·6	26·1	26·4
10	23·7	23·5	23·7	23·8	23·9	24·2	24·4	24·8	25·4	25·8	26·2	26·7
11	24·3	24·2	24·2	24·2	24·4	24·5	24·7	25·1	25·3	25·6	26·0	26·3
12	24·3	24·1	24·0	23·9	24·1	24·3	24·4	24·5	24·8	25·1	25·3	25·6
13	24·5	24·4	24·4	24·6	24·7	24·8	24·9	25·0	25·1	25·2	25·4	25·5
14	24·6	24·5	24·8	24·9	24·9	25·1	25·1	25·1	25·2	25·2	25·3	25·3
15	24·5	24·6	24·7	25·0	25·1	25·3	25·4	25·6	25·6	25·6	25·4	25·3
16	24·5	24·6	24·8	25·1	25·4	25·6	25·9	26·1	26·2	26·3	26·1	26·0
17	24·2	24·3	24·6	24·9	25·2	25·6	25·9	26·2	26·4	26·5	26·2	26·1
18	24·0	24·2	24·5	24·9	25·4	25·9	26·4	26·8	27·0	27·1	26·8	26·5
19	24·0	24·2	24·5	24·9	25·4	26·0	26·5	27·1	27·5	27·6	27·7	27·3
20	24·0	24·1	24·3	24·6	25·1	25·4	26·1	26·6	27·1	27·7	28·1	27·9
21	24·0	24·2	24·3	24·5	24·7	25·0	25·6	26·1	26·9	27·4	27·7	28·0
22	24·2	24·2	24·4	24·5	24·7	24·9	25·3	25·8	26·4	27·0	27·4	27·9
23	24·4	24·3	24·3	24·5	24·6	24·7	24·9	25·3	25·8	26·2	26·9	27·3
24	24·4	24·4	24·4	24·6	24·7	24·7	24·8	24·9	25·2	25·8	26·2	26·5
25	24·5	24·5	24·5	24·7	24·8	24·8	24·9	25·0	25·2	25·4	25·9	26·2
26	24·8	24·7	25·0	25·0	25·1	25·3	25·3	25·4	25·5	25·6	25·8	26·1
27	24·9	25·1	25·2	25·3	25·4	25·5	25·6	25·7	25·8	25·8	25·9	26·0
28	25·0	25·2	25·3	25·4	25·6	25·8	25·9	26·1	26·1	26·1	26·1	26·1
29	25·0	25·3	25·4	25·6	25·8	26·0	26·3	26·5	26·6	26·7	26·5	26·4
30	25·2	25·4	25·6	25·7	26·0	26·2	26·5	26·8	26·9	27·0	26·8	26·7
31	25·2	25·3	25·3	25·5	25·7	26·0	26·4	26·7	26·9	27·1	26·9	26·7

Scott Base—*Continued*

Month: July Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
24·9	24·8	24·7	24·7	24·8	24·8				25·4	25·7	26·2
25·2	25·2	25·2	25·2	25·2	25·2	25·2	25·2	25·2	25·4	25·6	25·9
25·0	25·1	25·2	25·3	25·4	25·3	25·3	25·4	25·4	25·5	25·6	25·7
24·9	25·2	25·4	25·6	25·7	25·8	25·9	26·0	26·0	26·0	26·0	25·9
24·9	25·2	25·5	25·9	26·1	26·3	26·4	26·5	26·5	26·4	26·4	26·3
24·4	24·6	25·0	25·3	25·7	25·9	26·1	26·2	26·4	26·5	26·5	26·2
24·1	24·2	24·6	25·0	25·4	25·8	26·1	26·5	26·7	27·0	26·9	26·6
24·2	24·5	25·0	25·3								
25·3	25·2	25·2	25·2	25·2	25·3	25·3	25·4	25·6	25·9	26·2	
25·3	25·2	25·2	25·3	25·4	25·5	25·5	25·6	25·7	26·1	26·4	26·8
25·3	25·3	25·4	25·4	25·5	25·5	25·5	25·5	25·6	25·8	26·2	26·4
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25·5	25·5	25·6	25·7	25·9	25·9	26·0	26·0	25·9	25·9	26·0	26·0
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25·5	25·6	25·7	25·9	26·1	26·3	26·4	26·5	26·6	26·6		
25·4	25·5	25·6	25·7	26·0	26·2	26·4	26·6	26·7	26·9	27·0	26·9
25·6	25·7	25·8	26·1	26·3	26·6	26·8	27·2	27·3	27·5	27·5	27·5
25·3	25·5	25·8	26·1	26·4	26·7	27·1	27·4	27·7	27·8	27·9	27·8
25·1	25·2	25·6	25·8	26·0	26·6	27·0	27·2	27·6	27·8	28·0	27·9

Month: December Year: 1957

13	14	15	16	17	18	19	20	21	22	23	24
25·8	25·6	25·5	25·2	25·2	25·1	25·3	25·4	25·2	25·1	24·9	24·7
25·9	25·6	25·4	25·0	24·8	24·7	24·7	24·7	24·7	24·5	24·4	24·3
26·2	26·0	25·7	25·4	25·2	24·9	24·8	24·7	24·6	24·5	24·4	24·3
26·8	26·7	26·4	26·0	25·7	25·3	25·2	25·0	24·9	24·7	24·5	24·3
27·1	27·0	26·7	26·4	26·0	25·5	25·3	25·0	24·5	24·2	24·0	23·9
26·6	26·4	26·1	25·7	25·3	25·0	24·7	24·3	23·9	23·7	23·5	23·4
27·0	26·8	26·7	26·5	26·2	25·8	25·4	25·1	24·7	24·3	24·0	23·7
27·3	27·1	27·0	26·9	26·7	26·5	26·1	25·7	25·3	24·7	24·5	24·0
26·7	26·8	26·9	26·6	26·5	26·3	26·2	25·7	25·3	24·9	24·5	23·9
26·9	27·1	27·2	27·0	26·9	26·8	26·7	26·3	25·7	25·3	24·7	24·5
26·5	26·7	26·8	26·6	26·5	26·5	26·3	26·0	25·6	25·0	24·9	24·5
25·8	26·0	26·1	26·1	26·1	26·2	26·0	25·7	25·5	25·2	24·9	24·6
25·7	25·9	26·0	26·0	26·0	26·1	25·9	25·8	25·5	25·2	24·9	24·7
25·3	25·4	25·2	25·1	25·1	25·1	25·1	25·0	24·9	24·7	24·5	24·3
25·2	25·1	25·1	25·0	25·0	25·0	25·0	25·0	24·7	24·5	24·4	24·3
25·8	25·5	25·3	25·1	24·9	24·8	24·7	24·5	24·3	24·1	23·9	24·1
25·9	25·6	25·2	25·0	24·7	24·5	24·4	24·3	24·0	23·8	23·6	23·9
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27·7	27·5	27·1	26·7	26·3	25·9	25·6	25·3	25·0	24·5	24·3	24·1
27·8	27·6	27·3	27·0	26·6	26·2	26·0	25·7	25·3	25·0	24·7	24·4
28·0	27·7	27·5	27·2	26·9	26·5	26·3	26·0	25·6	25·2	24·9	24·6
27·4	27·5	27·3	27·2	26·8	26·6	26·3	25·9	25·5	25·2	24·9	24·6
26·8	26·9	27·0	26·7	26·6	26·3	26·2	25·9	25·5	25·1	24·9	24·6
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26·2	26·2	26·3	26·3	26·3	26·3	26·1	26·0	25·7	25·5	25·2	25·0
25·9	25·8	25·8	25·7	25·7	25·7	26·1	25·8	25·6	25·5	25·2	25·1
26·2	26·0	25·9	25·9	25·8	26·0	26·1	25·9	25·8	25·6	25·4	25·2
26·5	26·2	25·9	25·7	25·5	25·5	25·5	25·4	25·4	25·2	25·0	25·0
26·5	26·2	25·7	25·5	25·3	25·2	25·1	25·1	25·0	24·9	24·9	24·8

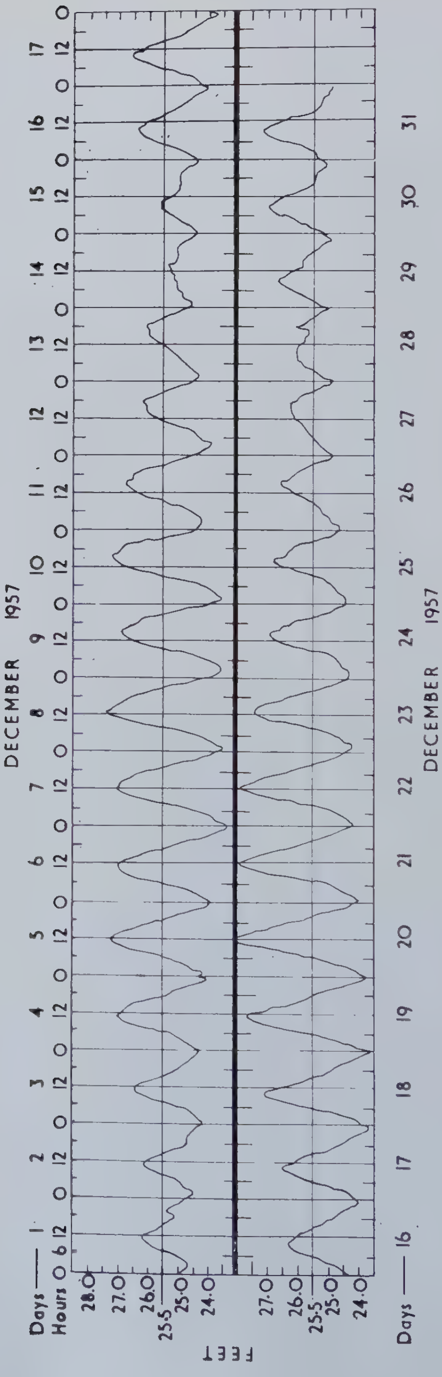

Fig. 9.—Sea-level for December 1957 (at Site 3).

TABLE 2.

Date	Time G.M.T.	Head of Water (ft)	Chart Reading (ft)	Difference (ft)
5/12/57	0150	24·6	15·7↑	8·9
5/12/57	2130	24·6	15·6↑	9·0
9/12/57	2125	24·6	16·1↓	8·5
25/12/57	2215	25·3	16·6↓	8·7
30/12/57	2140	25·3	16·6↓	8·7
31/12/57	2340	27·4	18·6↑	8·8
5 /1/58	1140	27·4	18·8↓	8·6

↑ = rising tide ↓ = falling tide

From these results it has been assumed that the recorder now has backlash and to get a true value of the height of water above the diaphragm, 8·9 ft has to be added to the chart reading if the tide is on the increase and 8·7 if it is on the decrease.

It is not intended here to give an analysis of the results, but the December values are presented graphically (Fig. 9) to show two points of interest: the diurnal character of the tide, i.e., one high and one low tide every 24 hours (approx.); and a second phase, which appears noticeably during the first few days of the month, the 12th to the 15th, and the 27th to the 29h.

ACKNOWLEDGEMENTS

The writers wish to thank Messrs J. W. Brodie and A. E. Gilmour of the New Zealand Oceanographic Institute for constructive criticism of the manuscript.

THE SUB-TROPICAL CONVERGENCE IN NEW ZEALAND SURFACE WATERS

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(Received for publication, 18 December 1958)

Summary

The geographical configuration and hydrological character of the sub-tropical convergence, the boundary between waters of sub-tropical and sub-antarctic origin, in the vicinity of New Zealand are discussed. As a background to this discussion some data are given on the seasonal variation of surface temperature in New Zealand coastal waters. The convergence follows approximately the isotherms of 15° C in February and 10° C in August and the isohalines of 34·7 to 34·8‰ with little seasonal variation. It is characterized at the surface by steep horizontal gradients of temperature and salinity. Off the west coast of New Zealand surface water seems to be predominantly sub-tropical in character, in Foveaux Strait and off South Island being probably derived from the East Australian Current, with the northern area probably subject at times to direct entry of sub-tropical water from the north-east of New Zealand. Wind-induced upwelling may often result in lowered temperatures close to the west coast of North Island, and pronounced drops in surface temperature are consistently found between the Three Kings Islands and the mainland, and off Cape Farewell. South of New Zealand sub-tropical influence is felt in sufficient degree to raise significantly the temperature and salinity of surface waters over the Campbell Plateau. East of South Island, sub-antractic water lies off the Otago coast and extends northwards along the east coast in a narrow band as far as the Castle Point region, North Island, where the sub-tropical convergence tends to meet the coast. From this point the convergence is well defined and trends sharply southwards under the action of the East Cape Current, tongues of sub-tropical water tending to come close inshore in southern Cook Strait and off Kaikoura. Offshore from the Banks Peninsula area the convergence trends eastwards towards the Chatham Islands and probably becomes less well defined at the surface. An area of probable upwelling is noted to occur frequently between East Cape and the Ranfurly Bank.

INTRODUCTION

Two oceanic surface water characteristics predominate in the New Zealand region:

SUB-TROPICAL WATER—water with relatively high temperature and salinity is formed in low latitudes of the eastern South Pacific. Its dominant characteristics are derived directly from the sun's heat. This water is driven westwards by prevailing south-easterly winds until deflected by land masses and bottom topography into higher latitudes of the south-west Pacific contributing, notably, to the East Australian Current, and to the East Cape Current of New Zealand. Because of climatic differences and mixing between tropic and temperate regions, water temperature and salinity are lowered with increasing latitude.

SUB-ANTARCTIC WATER—this water derives its relatively low temperature and salinity from the sub-antarctic region of the Southern Ocean where low air temperatures and an excess of precipitation into, over evaporation from the sea prevail. The westerly winds prevailing in this region give rise to a general east-going zonal movement called the West Wind Drift.

THE SUB-TROPICAL CONVERGENCE—the boundary between sub-tropical and sub-antarctic water has been called the *sub-tropical convergence*, the characteristics of which in New Zealand surface waters will be discussed in this paper.

PREVIOUS WORK

Description of the form of the sub-tropical convergence in the South Pacific has been due chiefly to Deacon (1937, 1945). A sharp change in surface temperature and salinity found across the boundary between sub-tropical and sub-antarctic water was considered to be maintained by convergent motion between meridional components of surface currents. The middle temperature of the boundary was reported at about 57° F (14° C) in summer and 50° F (10° C) in winter, and the salinty around 34·9‰ with little seasonal variation. Vertical sections of temperature and salinity across the boundary in the open ocean have given an indication of the meridional sub-surface circulation. The denser sub-antarctic water tends to sink at the convergence, but is turned back towards the south between depths of 200 and 300 ft (60 to 90 m) as a sub-surface current carrying a mixture of sub-tropical and sub-antarctic water, which in places has been followed almost to the Antarctic Convergence. Near the convergence, both sub-tropical and sub-antarctic water have strong east-going components. It was suggested that the convergence undergoes large seasonal north-south movements. In summer, the lighter surface water accumulating at the convergence pushes southwards, overlying a tongue of sub-surface sub-antarctic water. In winter, with sub-tropical currents weaker, the convergence moves northwards. Large non-periodic fluctuations have also been recorded.

From studies of the faunal distribution in New Zealand waters, Fleming (1944, 1952, and discussion following Deacon (1949)) was led to the idea of a wide belt of mixed waters lying between sub-tropical and sub-antarctic waters in the New Zealand region. Deacon (1945) has suggested that the idea of a convergence *region* may be useful "if it is recognized that the region is one over which sharp boundaries fluctuate, rather than one of gradual transition".

It was suggested by the writer (Garner, 1954) that surface water off the west coast of New Zealand was of sub-tropical origin derived from the East Australian Current, while sub-tropical water was shown to the east of the country as a tongue extending southwards between New Zealand and the Chatham Islands (see also Garner, 1953, 1957).

Figure 1 shows the general geographical trend of the sub-tropical convergence as derived from these studies.

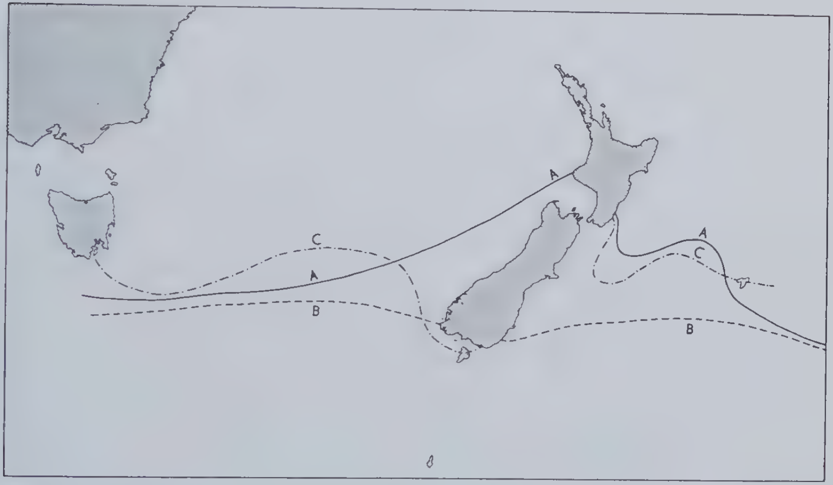

FIG. 1.—The New Zealand region showing (A) the trend of the sub-tropical convergence according to Deacon (1937) and (B) the southern limit of a zone of mixed waters which Fleming (1944) described between sub-antarctic water to the south and sub-tropical water north of A. C. is the general form of the convergence as suggested by Garner (1954).

TERMINOLOGY

Before discussing the available data, some amplification is made of terms given preliminary definition above.

The term *convergence* usually describes the boundary between two opposing current components at which one or both sinks below the surface setting up a vertical circulation system. This boundary may, or may not be associated with a sudden change in water properties, depending on the origin of the currents concerned, but in most cases, a convergence results in the development of a frontal surface between two different water masses.

A sharp temperature boundary at the surface does not necessarily involve the vertical circulation pattern associated with a convergence as defined above, the relative motion of water masses on each side of the boundary often being confined to a horizontal plane parallel with the boundary, especially in shallow coastal waters where development of vertical circulation is inhibited. It will be convenient here to retain the use of the term *sub-tropical convergence* for the boundary between sub-tropical and sub-antarctic water, so long as the word *convergence* is interpreted in its literal sense, as simply a "coming together" of two different water masses leaving room for further consideration of the velocity structure in a vertical cross-section at the boundary.

The terms *sub-tropical* and *sub-antarctic* may require qualification when near coastal waters are considered. Oceanic sub-tropical waters lie between the tropical water of the South Equatorial Current and the sub-tropical convergence, while sub-antarctic water lies between this boundary and the Antarctic Convergence. In general, surface temperature and salinity fall steadily with increasing latitude, more rapid changes being evident at the current boundaries and convergences. Modification of nearshore water properties may occur. Shallow or semi-enclosed waters may undergo large changes in temperature under local climatic effects, turbulent flow in tidal waters may induce intense vertical mixing of colder sub-surface and near-surface layers, and the run-off of fresh water from adjacent land will modify the temperature and salinity pattern in some areas. The formation of "slope" water over the continental slope through the mixing of oceanic and coastal shelf waters may be another source of complex surface gradients, and areas of cold surface water have been found associated with upwelling at some parts of the coast. The temperature boundary associated here with the sub-tropical convergence is usually quite distinct, however, and the terms *sub-tropical* and *sub-antarctic* will be applied, respectively, to the warmer and colder water on each side of this boundary. Some refinement of terminology of water properties and movements around New Zealand may be helpful when more information is available than at present.

DISCUSSION OF DATA

The new data presented in this paper are not sufficiently interrelated to be usefully catalogued here, and will be described in the discussion following. They consist of spot measurements of surface temperature and salinity, and continuous temperature records from surface thermograph collected by commercial and naval vessels.

SURFACE TEMPERATURE VARIATION IN NEW ZEALAND COASTAL WATERS

Monthly mean surface temperatures from observations returned from commercial vessels during 1950 (mostly from the fleet of the Union Steamship Company of New Zealand) were calculated for a number of areas traversed frequently by coastal shipping. An index of these areas appears in Fig. 2 and the sea temperature curves in Fig. 3. These were drawn from material prepared by G. F. Russell. Areas chosen contain about 20 reliable observations for each month, these being part of the data used in a study previously published (Garner, 1954).

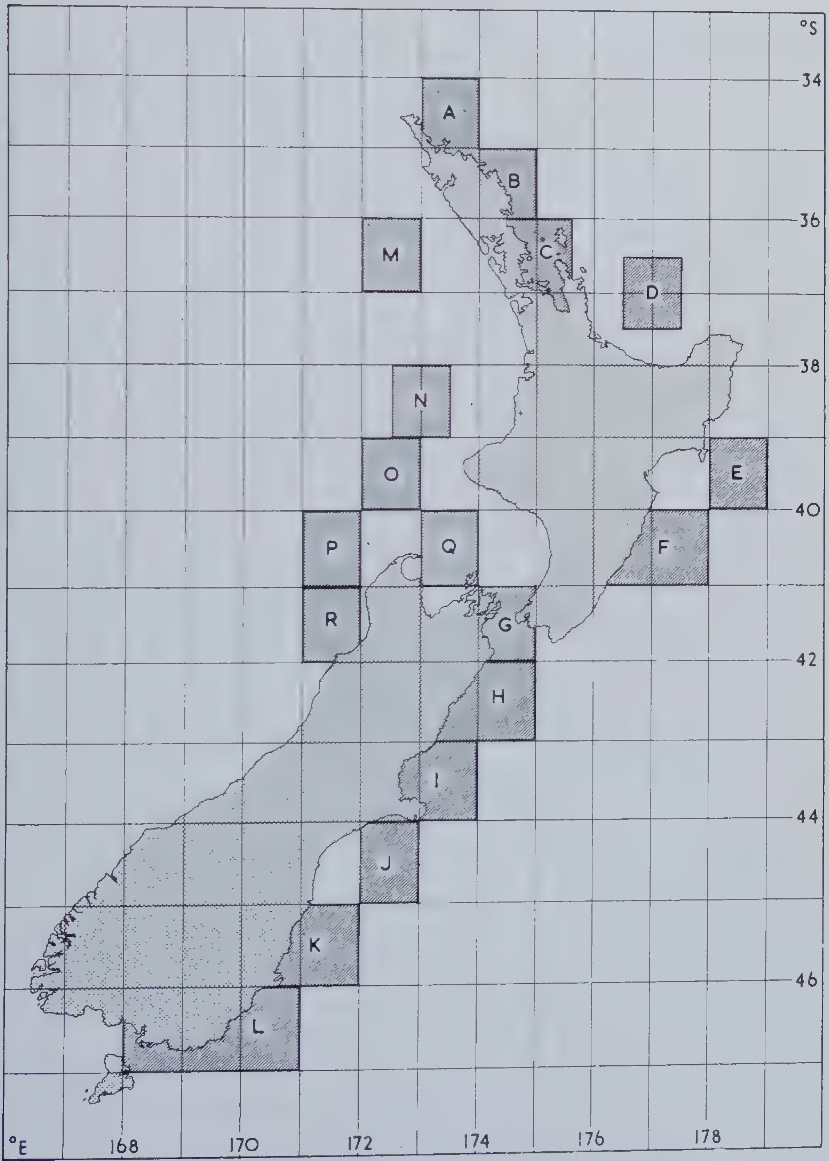

FIG. 2.—Index of New Zealand coastal areas referred to in the seasonal temperature curves of Fig. 3.

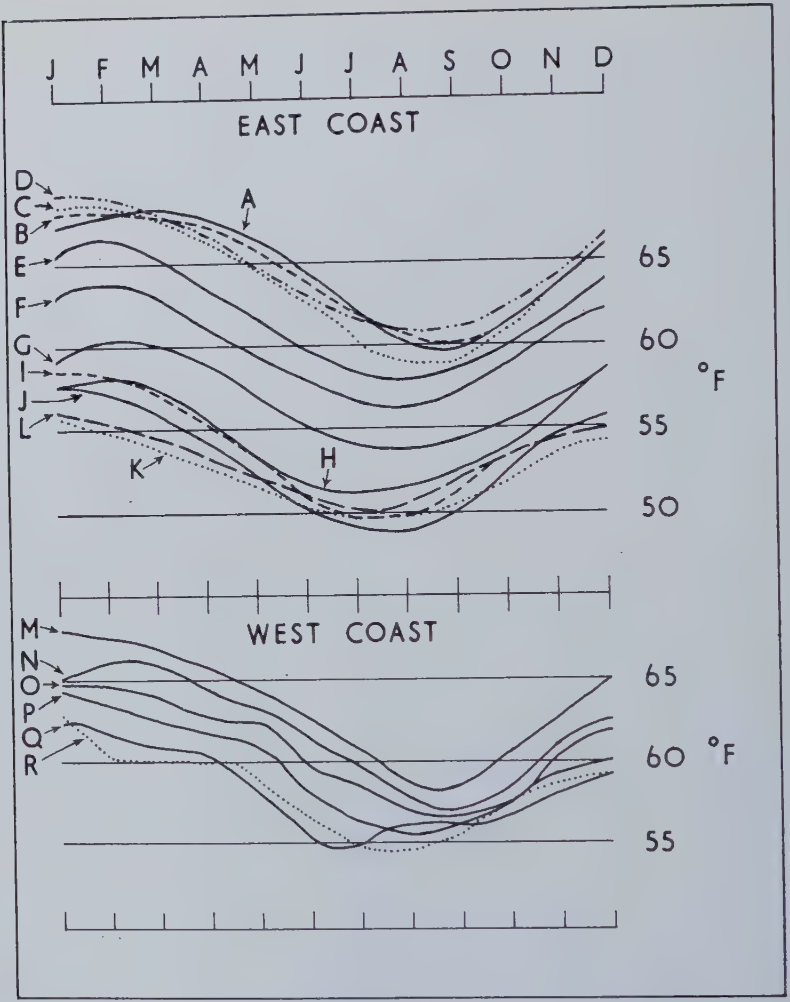

FIG. 3.—Seasonal variation in sea surface temperature (° F) in several areas off the New Zealand coast, an index to which appears in Fig. 2.

East Coast

MEAN ANNUAL TEMPERATURES—the annual mean temperature was about 64° F (17·8° C) between North Cape and the Hauraki Gulf. A slightly higher value (65° F; 18·3° C) was found in the Bay of Plenty, while between Hawke Bay and Kaikoura the mean temperature dropped sharply with increase in latitude to just over 54° F (12·2° C). Between Kaikoura and Foveaux Strait, the decrease was more gradual, the mean temperature falling to just below 53° F (11·7° C) in this last area.

ANNUAL TEMPERATURE RANGE—the range in mean monthly temperature tended to lie around 8½° F (4·7° C). High ranges of about 10° F (5·5° C) were recorded in the Hauraki Gulf, Pegasus Bay, and the South Canterbury Bight, and from the relatively enclosed nature of these waters due to the local coastal configuration, this was probably the cumulative effect of insolation in shallow water and coastal protection. Other areas covered by these data which at first sight might have been expected to show this effect are the Bay of Plenty and southern Cook Strait. The former area had a normal annual range of some 8½° F (4·7° C) and so the somewhat higher mean temperature recorded for this area seems to imply that the bay was subject to the direct entry of sub-tropical water from the warm tongue of water lying off the east coast (Garner, 1954). Southern Cook Strait, on the other hand, showed a relatively small annual range of about 6½° F (3·6° C) which could be due to a high degree of mixing of surface and colder deeper waters due to the action of winds and the interaction of strong tidal streams and irregular bottom topography—features which are not characteristic of the embayments with large seasonal temperature ranges. Other areas with smaller temperature ranges were off Kaikoura (7° F; 3·9° C), off the Otago coast (6° F; 3·3° C), and in Foveaux Strait (5½° F; 3·1° C).

EXTREME VALUES—Maximum mean monthly temperature occurred in January or February without any obvious systematic geographical differences. Minimum values tended to appear later in more northern waters (late August or early September) than further south (late July or August) down to Banks Peninsula, but the tendency seemed to reverse south of this area. This may be due to meteorological and other factors, but the suggestion is contained here of a convergence in coastwise movements in the region of Banks Peninsula. The coastal area between Hawke Bay and the north Canterbury coast was certainly one of transition relative to the waters north and south according to the rapid change of mean temperature with latitude, and it is in this area that is usually found the boundary between cooler inshore waters and the warmer mass in the East Cape Current.

West Coast

Data from areas off the west coast of New Zealand were not so extensive as for the east coast, being confined to a line offshore from Kaipara Harbour south to Cape Foulwind. At comparable latitudes, the west coast temperatures were about 1° F (0·6° C) lower than those off the east coast south to the western approaches of Cook Strait (but the areas involved are much further offshore than their east coast counterparts). South of this point, indications were that west coast waters were considerably warmer than those off the east coast. A pronounced drop in the level of mean temperature was found between the areas off Capes Egmont and Farewell, and it is noted that this is the area in which Deacon (1937) has drawn the sub-tropical convergence off the west coast of New Zealand (Fig. 1). The mean annual temperature range was about 10° F (5·5° C) in the northern area (off Kaipara Harbour) and it decreased to some 6° F (3·3° C) off Cape Foulwind. The high ranges north of Cape Egmont reached a level that was associated with shallow sheltered waters off the east coast. This explanation obviously does not apply to the oceanic areas off the west coast, and it seems that a seasonal change in the circulation pattern may involve the advection of warmer water into the area during the late summer and autumn months resulting in the un-symmetrical shape of the curve of seasonal variation. Higher temperatures were evident over this period resulting in a relatively slow decline in temperature from the summer maximum, and a delay till September in the winter minimum. This effect was also reflected, to some extent, in the seasonal curves for the two northernmost east coast areas, implying some sort of continuity between these waters in this respect. The three seasonal curves for areas south of Cape Egmont were also distinct in shape with earlier minima around June, and relatively slow recovery to summer maxima. The summer/autumn incursion of warmer water in the two northern areas persisted further south as an inflexion in the seasonal curve around April/May.

THE SUB-TROPICAL CONVERGENCE WEST OF NEW ZEALAND

The islands of New Zealand, occupying about 13 degrees of latitude at a distance of some 1000 miles from the east Australian coast must exert a controlling influence on the behaviour of sub-tropical water in the south-west Pacific. While little is known of the hydrology of the eastern Tasman Sea, it has come to be regarded as dominated at the surface by the north-going section of an anti-clockwise gyral of predominantly sub-tropical water in the Tasman Sea. Variations in this pattern might be expected in terms of direct entry of sub-antarctic water into the South Tasman, and of sub-tropical water from the north-west of New Zealand.

Discovery II Investigations, 1932

Deacon (1937) stated that the sub-tropical convergence was ill-defined in the Tasman Sea, attributing this to small meridional current components, flow being directed eastwards by the Australian continent. From the evidence available, however (two approximately meridional sections of temperature and salinity, one east of Tasmania and the other off the west coast of New Zealand; see Figs 1, 4, and 5) the convergence in the Tasman Sea was drawn from a position south-east of Tasmania towards Cook Strait, New Zealand. At *Discovery II* station 923, south-west of New Zealand, Deacon regarded the surface water as belonging to the sub-antarctic West Wind Drift, but found a large degree of sub-tropical influence evident at station 924 ,about

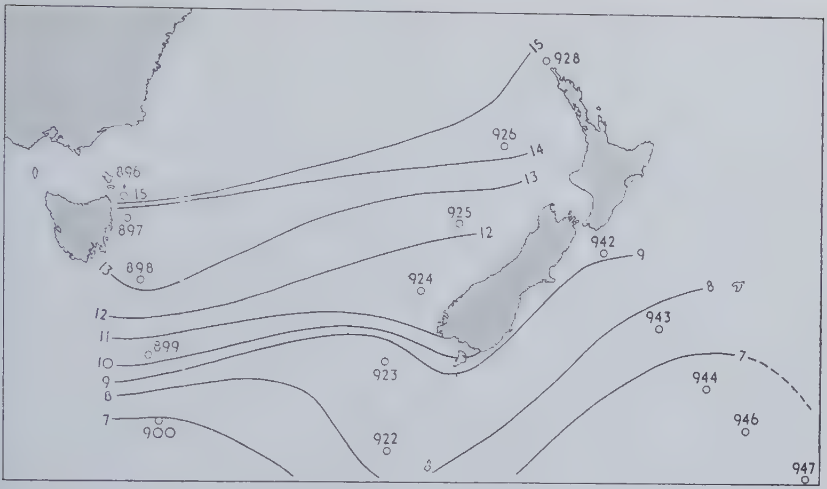

FIG. 4.—Trend of surface isotherms (° C) in the New Zealand region based on *Discovery II* stations worked in winter 1932 (Deacon, 1937).

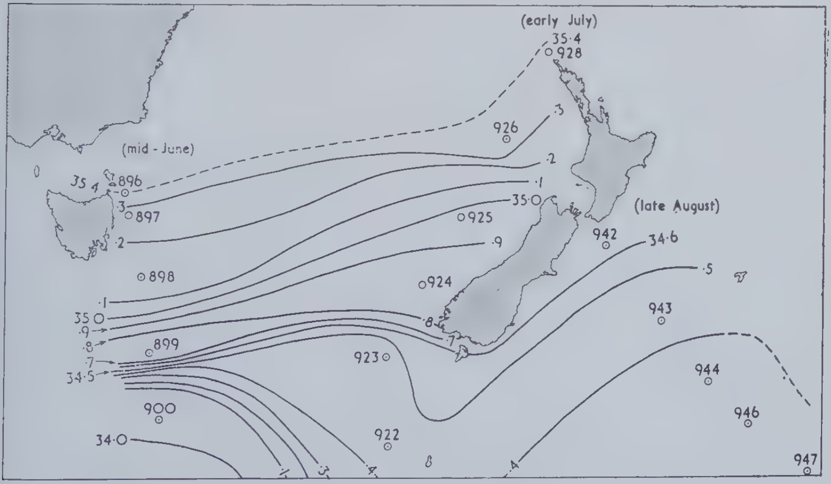

FIG. 5.—Trend of surface isohalines (‰) in the New Zealand region corresponding to the temperature distribution of Fig. 4.

80 miles west of Jackson's Head, south Westland. However, the convergence was drawn passing between stations 924 and 925 meeting the coast around Cape Egmont. Deacon regarded the area lying between the convergence and the west coast of South Island as subject to subantarctic influence, "possibly from upwelling of sub-surface Antarctic

Intermediate water". The isolines of 12° C (53·6° F) and 34·9‰ were used to trace the path of the convergence, and it was supposed that most of the sub-antarctic surface current passed eastwards through Cook Srait. In Figs 4 and 5 the surface data from Deacon's vertical sections are presented in charts of horizontal distribution. Care must be taken in viewing these charts in terms of synoptic patterns as the effects of seasonal variation will be contained in the isoline patterns as drawn here (June-July-August). The two Tasman Sea sections were, however, separated by only about two weeks and thus should be comparable in general detail. Looking for a convergence on these charts in terms of a general steepening of the meridional gradient in surface properties, the isolines of 10° C (50° F) and 34·7‰ seem, to the writer, to mark approximately the course of the boundary between sub-tropical and sub-antarctic water. The geographical trend of these lines is similar to that derived from recent studies by the writer and sketched in Fig. 1 (line C). It would seem that here, too, is evidence for an overall sub-tropical influence on the whole west coast of New Zealand, the flow off South Island being north-going in general, with a branch extending into Foveaux Strait from the west. A note of historical interest and probable relevance here has been recorded by Turnbull (1875), who identified wreckage found on the eastern bank of the Tauperikaka River, about 3 miles south of Arnott Point, as part of the remains of the *Schomberg*, wrecked on Moonlight Head, south coast of Australia, in 1854. Drift across the south Tasman Sea in a "derivative of the East Australian Current" was postulated. The divergence north and south of flow off the South Westland coast which has been mentioned by the *New Zealand Pilot* since its first edition in 1856 (p. 248) is thus visualized here as occurring north of the sub-tropical convergence rather than in sub-antarctic water as described by Deacon. While there obviously exists a northward trend to isolines from the western to the eastern Tasman Sea on the charts derived from *Discovery* data, with sections confined to near coastal areas on each side of the Tasman, a considerable amount of presumption is involved in showing the path followed by isolines across the central Tasman Sea, and Figs 4 and 5 have been drawn keeping in mind the writer's previous studies of isotherm configuration in this area (Garner, 1954). South-east of Tasmania, it will be noticed (Fig. 4) that between undoubted sub-tropical influence at station 898 and sub-antarctic influence at station 900, a broad band of relatively rapid temperature change between 8° C (46·4° F) and 12° C (53·6° F) is evident centred on station 899. Only the central part of this band, between 9° C (48·2° F) and 11° C (51·8° F) appears in the eastern Tasman Sea, remaining part of a pronounced surface gradient which is here associated with the sub-tropical convergence. Some peculiarities evident in the area south of New Zealand will be discussed later. The pattern of surface salinity (Fig. 5) resolves the band of pronounced gradient in surface properties south-east of Tasmania in more detail. The steepest gradient is found in the southern part of the band, between

34·1‰ and 34·8‰, the highest salinities here being associated with the sub-tropical convergence, and the very steep gradient probably resulting from strong convergence between the East Australian Current and the West Wind Drift. A secondary band of rapid change in salinity appears to the north of station 899 between the isohalines of 34·9‰ and 35·1‰. It is possible to re-draw the salinity pattern of Fig. 5 to maintain the steep gradient between these isohalines, this secondary band (dotted lines) then following closely the convergence trend as originally drawn by Deacon. The suggestion is contained here of a secondary convergence in the eastetrn Tasman Sea between, say, a direct entry of sub-tropical water from north-east of New Zealand and a north-going movement of Tasman water of sub-tropical origin. Further comment on this question must await the collection of more data. The observed movement of coastal debris along the west coast of South Island calls for a general north-going set (part of which will be a wave-induced litteral drift) (Furkert, 1947) and a pronounced indraught into northern Cook Strait from the region east of Cape Farewell has been recorded (Marine Department records; and see "Evening Post", Wellington, 8/6/53). An interesting historical allusion to this movement is found in the log of D'Urville's exploration of the New Zealand Coast in 1827. On 13th January he recorded (translation by Smith (1907, p. 421)) ". . . at 7 p.m. we were on the parallel of Cape Farewell and three or four miles off it. The night was tranquil, and we spent it making short tacks with a nice westerly wind". For 14 January is recorded: "At 3 a.m. I steered in the direction where I presumed Cape Farewell lay; but at daylight I perceived that the current during the night had carried us far to the ENE and and we were already considerably within the Straits."

Figure 6 shows the distribution of temperature to a depth of 200 ft (137 m) and surface salinity along a course westwards out of Cook Strait and northwards along the west coast of North Island to the Three Kings Islands from bathythermograph soundings and water samples taken by H.M.N.Z.S. *Lachlan* in October 1951. North of Cape Egmont there was little feature shown in the distribution of water properties. To the north-west of Cape Farewell, however, a well defined band of cold water was present at surface overlying warmer deeper water. This had probably been introduced through an upwelling movement at the shelf edge to the south, before noted (Garner, 1954) as a frequently observed feature in this area. Colder water was also observed in the *Lachlan* section west of Cape Egmont, and both this area, and that off Cape Farewell were associated with a lowering of surface salinity.

No trace of a similar upwelling movement was observed around the Three Kings group, to the south of which is commonly found a low temperature anomaly in surface waters (Garner, 1954). The Three Kings area is recognized as a faunally distinct province, the Auporian,

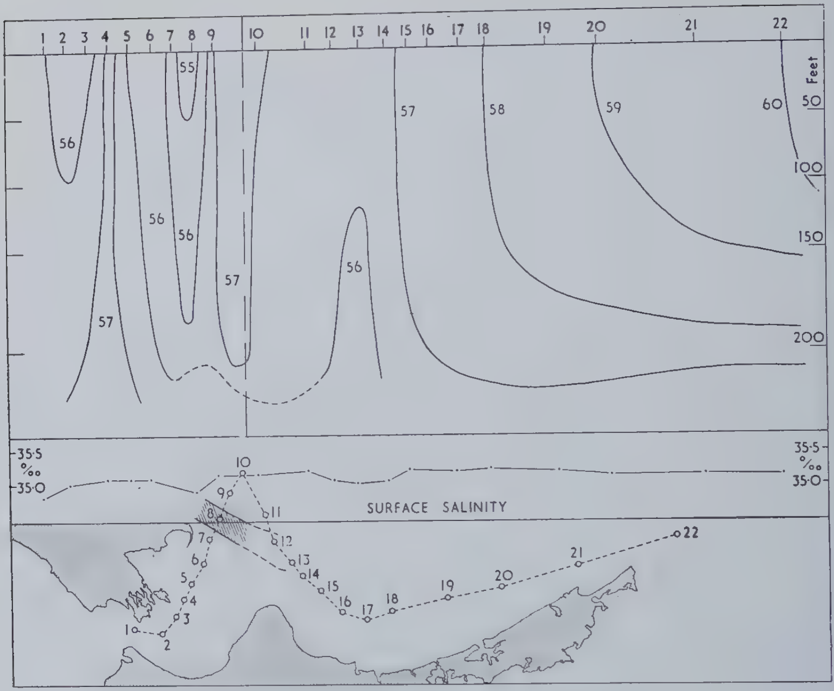

FIG. 6.—Vertical profile of temperature along a section off the west coast of North Island, New Zealand, based on bathythermograph soundings taken from H.M.N.Z.S. *Lachlan* (25-28 July, 1951) whose location is given in the lower frame. The centre section shows the variation of surface salinity along the track.

which Fleming (1944, p. 217) notes is ". . . well within the subtropical zone of surface water. . . . The presence of a distinct southern element in the fauna is suggestive of a sub-antarctic influence some time in the past". Bary (1952, p. 16) expresses as his opinion that the upwelled water around the Three Kings Islands "appears to be subantarctic water and to be carrying southern fauna northwards." The British Antarctic (*Terra Nova*) Expedition carried out a comprehensive winter survey of plankton in the area. From the distributoin of dead and decaying plankton in the shallower water around the Three Kings Islands, Garstang (1933, p. 238) suggested the existence of upwelling of deep water against the northern edge of the shelf, probably under the influence of a current setting from the north or north-east. He considered that there was little evidence to suggest upwelling on the southern side, from the Tasman Sea. The associated hydrological observations do no appear to have been published. Commander A. L. Lawford kindly supplied the writer with relevant data contained in Notebooks of the D. J. Matthews collection (now in the library of the

British National Institute of Oceanography). In view of the general importance of these figures, they are quoted here in Table 1. From the surface temperature charts of Garner (1954) an average temperature around the Three Kings region would be about 60° F (15·5° C) for the period of the *Terra Nova* work. Fig. 7, plotted from the data of Table 1, shows that apart from a few anomalies (probably due to errors of measurement) temperature values lower than this fall on a characteristics T-S curve whether referring to surface or to deep samples.

TABLE 1.—Hydrological Observations in the Vicinity of the Three King Islands taken by the British Antarctic (*Terra Nova*) Expedition 1911.

Values marked * are anomalies on the T-S plot of Fig. 9.

Date	Time (M)	Lat (S)	Long (E)	Depth (m)	Temp (°C)	Salinity (‰)
17/7/11	0930	34° 08′	172° 04′	0	14·60	35·34
21/7/11	1230	34° 35′	171° 16′	0	15·72	35·43
23/7/11	1112	34° 25′	171° 40′	10	15·76	35·41
				25	15·58	35·43
				50	15·32	35·37
				100	14·78	35·32
				130	14·52	35·35
24/7/11	1000	34° 23′	172° 07′	0	15·82	35·44
25/7/11	1200	34° 20′	172° 08′	0	15·12	—
28/7/11	1400	34° 11′	172° 11′	10	14·40	35·26
				25	14·40	35·28
				50	14·31	35·32
				100	13·83	35·39*
2/8/11	0900	34° 54′	173° 34′	0	15·98	35·48
5/8/11	1630	34° 15′	172° 00′	10	14·21	35·57*
				25	13·60	35·25
				50	13·43	35·21
				100	13·00	35·23
				200	11·60	35·14
19/8/11	1200	34° 40′	172° 15′	10	14·60	35·41*
				50	14·45	35·28
				100	13·37	35·23
27/8/11	1300	34° 26′	172° 17′	10	14·90	35·28
				50	14·60	35·34
				100	13·98	35·30
18/9/11	1400	off North Cape		0	15·10	35·39
				10	15·12	35·41
				24	15·08	35·41
22/9/11	1600	34° 39′	172° 16′	10	14·70	35·19*
				50	14·67	35·34
				100	14·20	35·32
				160	13·48	35·34*

An Auckland Institute and Museum expedition to the Three Kings Islands in January 1951 found that surface temperatures fell steadily from 67·8° C (19·7° C) in Spirits Bay (between North Cape and Cape Reinga) to 60·8° F (16·0° C) off Great Island (personal communication from Mr E. G. Turbott). *The New Zealand Pilot* (11th

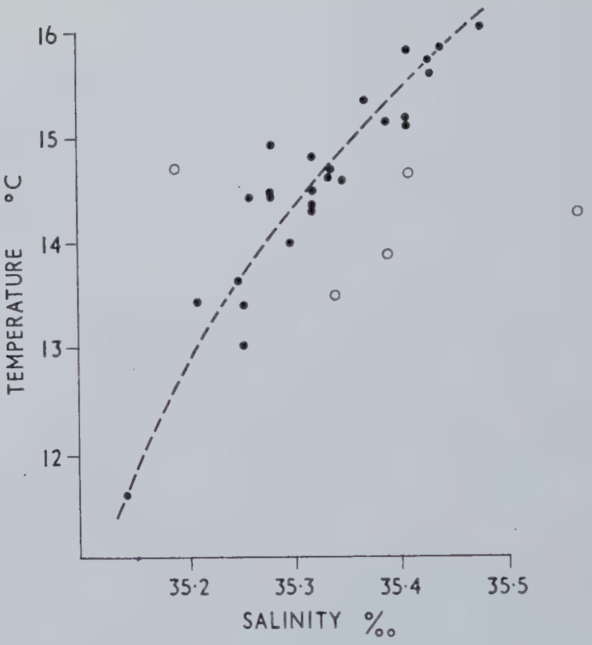

FIG. 7.—Temperature—salinity correlation diagram construction from the *Terra Nova* data listed in Table 1. Points plotted as open circles are marked * in the Table.

edit., p. 119) warns that "strong tidal streams, currents and races" occur between the Three Kings and the mainland, and that 3 to 5 knot tidal streams around the Islands "frequently give an appearance of shoal depths". A well-defined stream, with eddies and broken water marking the edges, and flowing towards the north-east at 1 to 2 knots, was found by Wilson (1950) to be four miles wide and 5° F cooler than the surrounding water a few miles off the Three Kings in November 1949. It might be expected that any upwelling pattern here would be dependent on the stage of the tide. Thermograph records taken within a short period of each other have shown large differences in the extent and definition of the cold water region, but there is insufficient data of this nature available to extract a tidal influence.

Whether the cold water often found near Cape Farewell and the Three Kings Islands are parts of a continuous band of upwelling along the west coast is not known. Cassie (1955) has remarked that such an occurrence would explain the frequent blooms of phytoplankton which seem to be associated with the toheroa (*Amphidesma ventricosum*) beaches on the west coast of North Island. Falla (1929, p. 13) remarked that ". . . it seems likely that a current of Antarctic origin affects the west coast (of North Island). This is suggested by the low summer temperature of the sea, the presence of giant kelp (*Durvillea*), of southern molluscs and of drift material containing Antarctic forms. On parts of the west coast, too, influence of the warmer East Australian Current may be observed together with the Antarctic influences already mentioned". These remarks may also refer to the effect of upwelling of deeper waters near the coast. Any coastal upwelling as widespread as this would probably be induced by a prevailing wind which tended to move surface water away from the coast. According to charts of mean sea level pressure published by de Lisle (1957), New Zealand lies wholly within the prevailing westerlies during spring and winter (June to November) showing a strong orographic effect with a marked windward ridge, especialy off the west coast of South Island. This wind system would tend to drive surface waters onshore. During summer and autumn (December to May) North Island lies within the influence of the sub-tropical anticyclone, and any easterly to south-easterly winds experienced during this period would tend to induce upwelling of colder water near to the coast.

THE SUB-TROPICAL CONVERGENCE SOUTH OF NEW ZEALAND

It has been suggested in the previous section that sub-tropical water derived from the Tasman Current may move into coastal waters south of South Island. Bary (1956, p. 442) implied that a level of salinity has been found in Foveaux Strait indicative of sub-tropical water moving in from the west. The extent to which this water may penetrate south and east is not known from existing data. The *Discovery II* sections south of the Tasman Sea show that both isotherms and isohalines bend sharply southwards south of New Zealand below 9° C (48·2° F) and 34·5‰. It is possible, however, that this is due to vertical exchange between surface sub-antarctic water and the subsurface sub-tropical current (which *Discovery II* sections—Deacon, 1937; Plates 29 and 32—show to be relatively strongly developed south of the Tasman Sea but only weakly in evidence south-east of New Zealand) in the relatively shallow water over the Campbell Plateau. The higher temperature and salinity south of New Zealand around *Discovery II* station 922 relative to values found further west suggests, as Deacon (1937) states, that the West Wind Drift is deflected towards the south. A deep gradient current moving into shallower water would tend to show a deflection to the left of its direction of flow (southern hemisphere) and such a deflection might be expected over the Campbell Plateau, south of New Zealand. Thus, other processes must be at work to produce the anomalous patterns observed in this area. Halligan (1921) spoke of a "branch of the East Australian Current flowing eastwards at high latitudes", Powell (1947, p. 3) mentions ". . . a warm water current which proceeds down the East Australian Coast and thence across the Tasman to influence water temperatures as far south as the Auckland Islands". No references to the sources of this information were given by either writer. The earliest reference to this idea that has come to the writer's notice is that of Mangin (1888, pp. 113, 116) who writes of "warm water passing between Australia and New Zealand" to the influence of which was attributed the relatively easy ice conditions which "permitted Capt. James Ross to push farther than any of his predecessors in the exploration of these inhospitable latitudes". While this idea may hardly bear analysis today, it will be interesting to see whether significant modification of the sub-antarctic climate may possibly be associated with hydrological processes over the Campbell Plateau. The flora of the sub-antarctic islands south of New Zealand show some striking features and while these will be due to a whole complex of ecological factors it may be relevant to examine the oceanographic aspect. The Snares are characterized by a vigorous growth of *Olearia lyallii,* the "mutton-bird tree" of Stewart Island. The Auckland Islands carry a relatively dense forest containing southern rata and *Coprosma* while further south, Campbell Island supports no true tree growth at all. Referring to the Snares, Murphy (1948) states ". . . in a zone where a visitor might expect to find antartcic beeches (*Nothofagus*) the dense "goblin-forest" is, on the contrary, made up of tree-composites of sub-tropical affinities". Cheeseman (1909) notes the occurrence on the coast of the Auckland Islands of *Gnaphelium luteo-album,* and remarks that the species is found remarkably far south here, as its general Southern Hemisphere distribution labels it as a tropical or warm temperate plant. It occurs on the sub-tropical convergence islands of Tristan d' Acunha and Inaccessible Island but not on Kerguelen or the Crozets where an undoubted sub-antarctic influence prevails.

The writer has earlier recorded (Garner, 1954) a sea surface thermograph record between Dunedin and Campbell Island showing a sharp temperature boundary south-east of South Island and a secondary maximum in surface temperature in latitude 50° S. Fig. 8 shows the distribution of surface temperature south-east of South Island based on this record and that taken farther to the east on the return voyage in April 1951. The temperature boundary marking the main feature of the sub-tropical convergence east of New Zealand was crossed off Banks Peninsula between about 56° and 61° F (about 13·5° and 16° C). A secondary well-defined line of steep temperature gradient, between about 51° and 54° F (about 10·5° and 12° C) lay over the northern edge of the Campbell Plateau, south-east of South Island, and this may well be continuous south of South Island with the sub-tropical convergence in the South Tasman Sea.

Fig. 9 records a further thermogram obtained between Dunedin and Auckland Islands by H.M.N.Z.S. *Tui* in November 1954. Relatively warm water influence is apparent as far south as 49° S (between Auckland and Campbell Islands surface temperature fell gradually by a further degree Fahrenheit), temperature boundaries being evident in

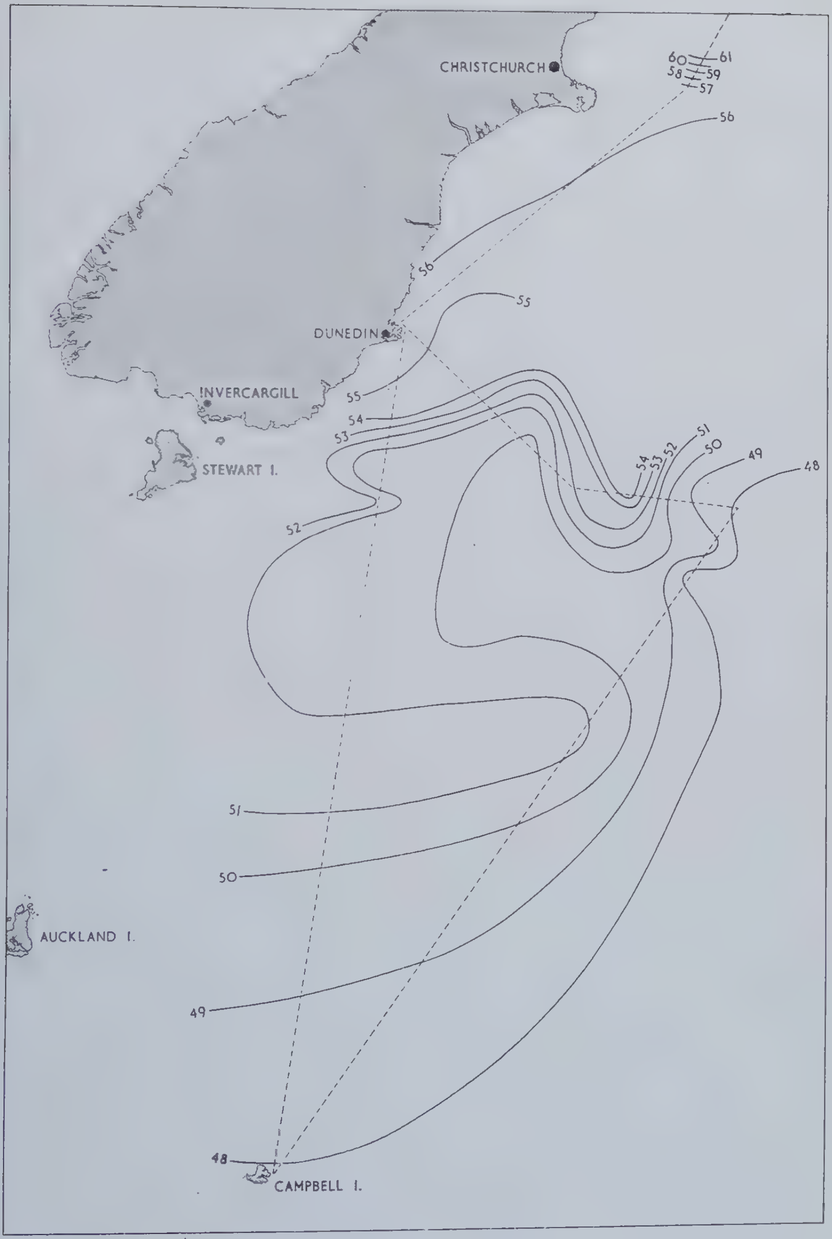

FIG. 8.—Distribution of sea surface temperatures over the Campbell Plateau plotted from thermograph records taken by H.M.N.Z.S. *Kaniere*, 19-27 April 1951.

47° S and $48\frac{1}{2}$° S. South of each of these marked gradients of surface temperature are isolated patches of warmer water, either parts of boundary eddies or masses of warmer water which have broken off from the parent body.

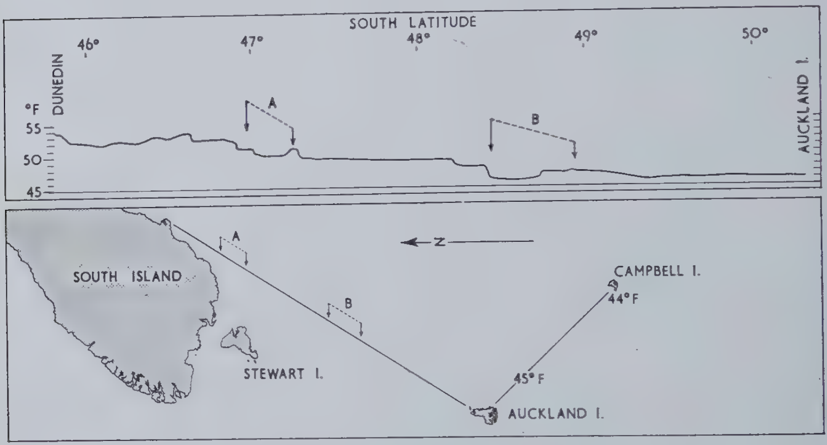

FIG. 9.—Surface thermograph record (upper frame) taken by H.M.N.Z.S. *Tui* between Dunedin and the Auckland Islands (lower frame), 5-9 November 1954.

THE SUB-TROPCAL CONVERGENCE EAST OF NEW ZEALAND

Krummel is quoted (*in* Deacon, 1937) as suggesting that north-going sub-tropical water west of North Island turns around North Cape during the winter months forming part of the south-going flow past East Cape. In summer it was suggested that the flow turned back into the north Tasman Sea completing the clockwise gyral. This recalls the previous section here on seasonal temperature variations where it was noted that there appeared to be advection of warmer water into the region west and north-east of North Island during the late summer and autumn months. Fuller (1953), on the other hand has noted a seasonal variation in surface salinity of the outer parts of the Hauraki Gulf in 1950 rising from 35·3‰ in November to 35·7‰ in July. The distinct plankton communities found in the high and low salinity waters respectively suggested that the Gulf was under the seasonal influence of surface water from two different sources and it was supposed that high salinity water from the Tasman Sea flowed most strongly into the area during the winter season. In that surface temperatures off the east coast of North Island around this period tended to be higher than those off its west coast, the writer (Garner, 1954) supposed that sub-tropical water was entering the east coast cirulation directly from the north-east of New Zealand. Fleming (1950, 1952) noted the existence of a pronounced tongue of warm surface water lying between New Zealand and the Chatham Islands and ascribed this to a south-going water movement which he called the East Cape Current. Deacon (1937) also showed a similar trend of the sub-tropical convergence in this area (see Fig. 1 of this paper).

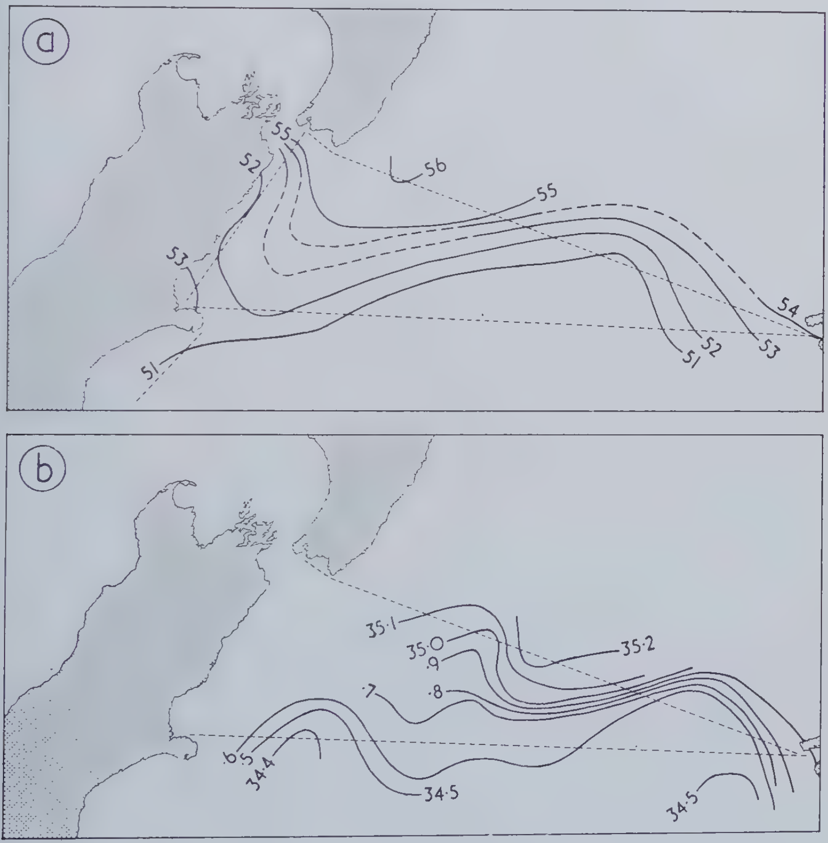

FIG. 10.—Distribution of surface properties between New Zealand and the Chatham Islands:
(a) temperature, M.V. *Port Waikato*, May 1951
(b) salinity, N.Z.G.S. *Matai*, September 1951

Patterns of surface temperature and salinity between New Zealand and the Chatham Island (e.g. Fig. 10 and Garner, 1957) show a tendency for sub-antarctic water to push northwards separating tongues of sub-tropical water near New Zealand and the Chatham Islands. The temperature distribution between Wellington and Lyttelton consistently shows tongues of warm water in southern Cook Strait and off Kaikoura (Garner, 1953). A further sharp break in the temperature gradient (Fig. 11) off the east coast of North Island, usually near Castle Point is used to derive the general geographical trend of the sub-tropical convergence to the east of New Zealand as shown in Fig. 1, line C. Lines A and C in this figure are virtually the same except that recent observations indicate that the effect of the East Cape Current is usually more pronounced than Deacon's map indicates.

A feature of the thermograms of Fig. 11 is the pronounced temperature drop off East Cape, which like similar temperature structures found off North Cape and Cape Farewell, suggests the existence of coastal upwelling, in this case, possibly by southward moving water impinging against the shelf edge which extends well offshore from East Cape out to the Ranfurly Bank. Several vessels passing through this area have reported the region of low temperature to be marked by a change in the colour of the water from blue to green, as if the "upwelled" water contained a considerable amount of bottom sediment.

From the fore-going discussion it would seem that direct sub-antarctic influence in surface water is probably confined in general to the south-east of South Island, between the sub-tropical tongue off Banks Peninsula and the Tasman Water in Foveaux Strait. Mixed sub-tropical/sub-antarctic influence will be felt on the cold side of the sub-tropical convergence in inshore waters between the Castle Point region and Banks Peninsula. Fig. 12 provides a convenient summary of the effect of varying hydrological influences on South Island coastal waters. The tongue of the East Cape Current is recognized between Cape Palliser and the south-east of Banks Peninsula south of which a sharp drop in surface temperature is evident. The single ship's-track south of Banks Peninsula is insufficient, of course, to permit the drawing of isotherms, but the pattern shown indicates the temperature level measured and the probable temperature structure in the area guided by earlier work. South of the Otago Pninsula, the temperature gradually increases, and in Foveaux Strait has reached the temperature level at the sub-tropical convergence off Banks Peninsula. Warm water influence is marked along the whole of the west coast of the island but temperature falls fairly rapidly away from the coast.

ACKNOWLEDGEMENTS

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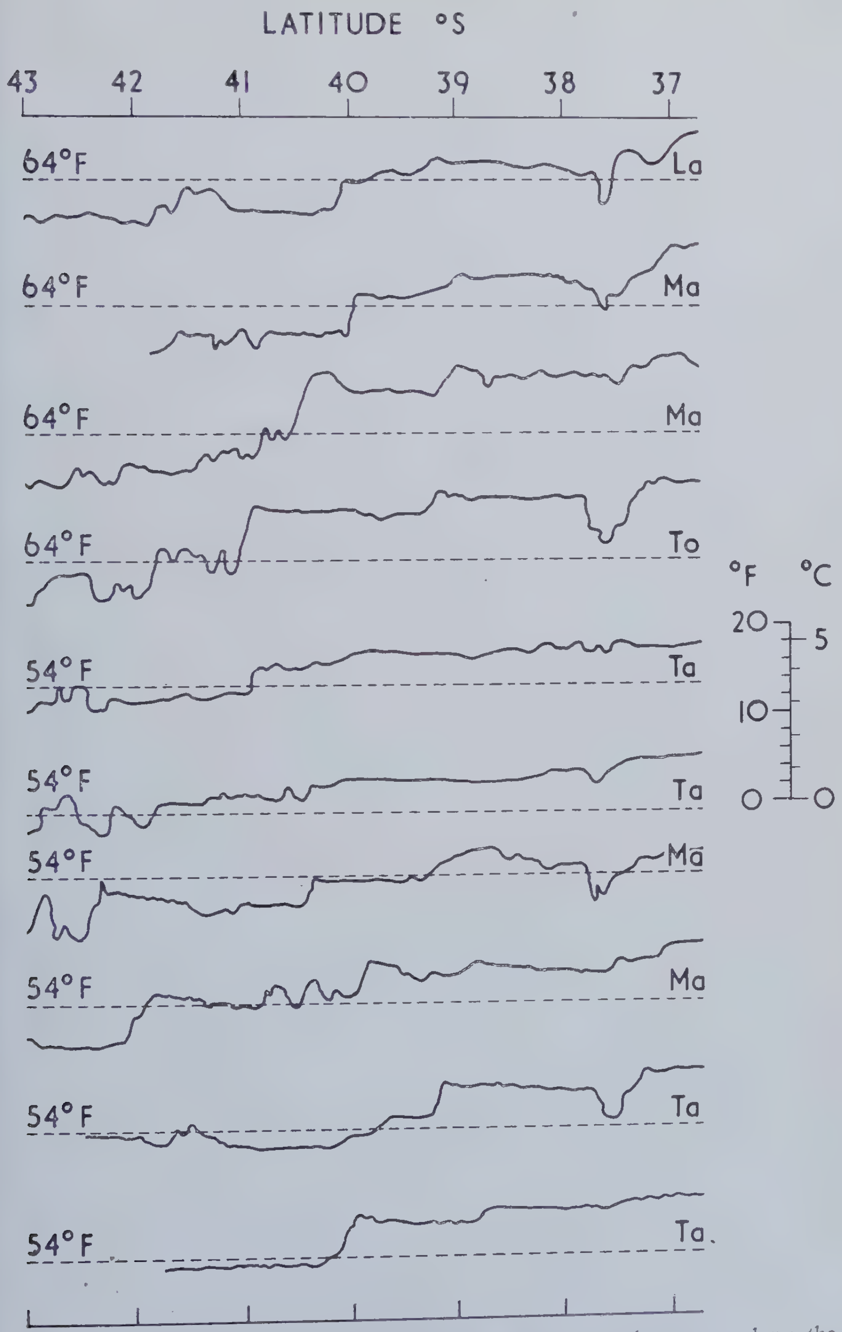

Fig. 11.—Sea surface thermograph records taken on coastal passage along the east coast of New Zealand between East Cape and the North Canterbury coast. A base temperature level is given with each trace and a relative temperature scale shown on the right. Dates at the mid-points of each trace are noted and the observing ships are shown as La—H.M.N.Z.S. *Lachlan*; Ma—M.V. *Matua*; To—M.V. *Tofua*; Ta—M.V. *Tanea*.

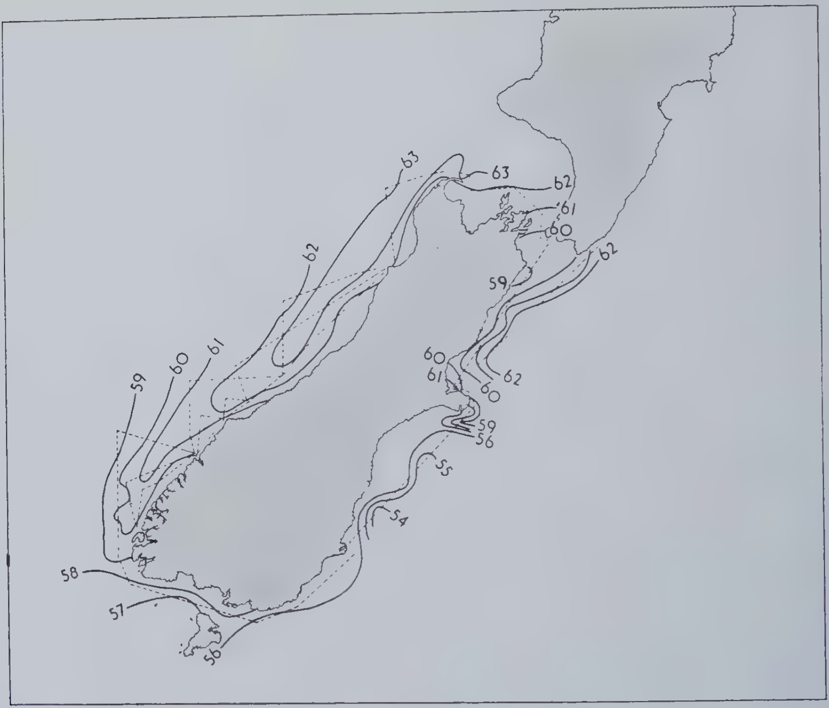

FIG. 12.—The distribution of sea surface temperature in South Island coastal waters from measurements made by H.M.N.Z.S. *Lachlan* (supplemented by M.V. *Tofua*, Lyttelton towards Cape Palliser) from 27 February to 17 March 1952.

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GENUS *LEPTALOSIA* DUNBAR AND CONDRA

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Summary

Genus *Leptalosia* is considered to be a young growth-form of *Strophalosia* or *Heteralosia. Etheridgina* Oehlert (1887), regarded as a senior synonym of *Leptalosia* by Prendergast (1943) and Coleman (1958), is productoid, unrelated to *Strophalosia.*

INTRODUCTION

Study of the growth-stages of *Strophalosia* affects the validity of *Leptalosia* Dunbar and Condra (1932). *Leptalosia* was proposed for small Strophalosiid species two to ten millimetres wide which are cemented to a foreign object by most of the ventral disc, unlike *Strophalosia* and most other Strophalosiids, which adhere by an umbonal cicatrice on the ventral valve. Internal features of the dorsal valve in *Leptalosia* are also apparently distinctive. Dunbar and Condra (1932, p. 260) stated that "the cardinal process is small and bifid, being composed of two narrow posteriorly facing and closely adpressed muscular apophyses, supported in front by a pair of very short diverging ridges separated by a depression". In *Strophalosia* and related genera the cardinal process from a ventral aspect is trifid, with a prominent median lobe that is apparently undeveloped in *Leptalosia*. In front of the cardinal process is a median septum, unmentioned and presumably absent from *Leptalosia.*

EARLY GROWTH STAGES IN NEW ZEALAND *Strophalosia*

Attitude of Growth

Tiny Strophalosiid specimens are present in the lower part of the Permian Productus Creek Group in Southland, and in the upper limestone of the correlative Maitai Group of Nelson. Over 300 specimens from two to thirty millimetres wide have been studied from one locality in the Productus Creek Group, chiefly by preparing polyvinol chloride moulds in vacuum from fossiliferous rock slabs leached in acid.

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In more than two-thirds of the specimens under ten millimetres wide the ventral valve is adherent over most of the visceral disc, with spines that radiate fan-wise over the host shell. These specimens resemble *Leptalosia* in habit. Other small specimens in the same fauna adhere by a cicatrice at the umbo so as to "stand on their heads", in the conventional attitude of *Strophalosia*. These shells may also be supported by spines which rest like struts against the host shell. From the habit of growth, therefore, both *Leptalosia* and *Strophalosia* are present.

Apart from attitude, the only known difference between the recumbent and the erect specimens is that when the recumbent shells are about six millimetres wide, the lateral and anterior margins may turn dorsally through about 45°, simulating a trail. This is not a true trail, but represents an attempt by the animal to lift the anterior margin above the substratum in order to gain a fresh supply of water similar to that available to the erect, more delicately balanced specimens. There are no other differences between the erect and recumbent shells in shape, ornament, or internal details. Judging from the comparison of the morphology of numerous specimens, both represent the young form of a single species of *Strophalosia*. Thus it appears that the position of growth for young *Strophalosia* varied from erect to recumbent and indeed a few small shells are found in an intermediate position, inclined at 40° to 60° from the substratum. Both erect and recumbent shells survived into maturity but as the shell grew, the recumbent specimens gradually became more erect, though they retained a larger scar of attachment than the shells developed from an erect young specimen. This partly explains the wide variation in the size of the cicatrice in mature *Strophalosia*. A few immature shells from 16 to 20 millimetres wide have been found inclined at only 10° to 20° from the sub-stratum, but most shells of this size were probably erect. In late maturity and senility, when the shell is about 25 millimetres wide, the shells generally tumbled on to the ventral valve.

Internal Details of the Dorsal Valve

In both the erect and recumbent specimens the dorsal valve underwent considerable change with increase in size. The important internal structures in the young shell lie on the nepionic area, two or three millimeters wide, which externally is convex, and lacks spines. Between the dental sockets is a cardinal process with well developed muscle apophyses. Seen from a ventral aspect ,the two lateral lobes of the process are unusually prominent, and continue into the short cardinal ridges, which are each declined at 45° from the hinge and lie in front of the dental sockets. A deep cleft lies between the two lateral lobes in the ventral face of the process, and the median lobe is inconspicuous. Thus the process closely resembles that of the mature *Aulosteges* (Prendergast, 1943, text fig. 4, p. 33), and apparently corresponds with that described for *Leptalosia* by Dunbar and Condra (1932, p. 260), quoted above. No median septum is present in these small specimens, again as in *Leptalosia*.

In larger shells, about 3·5 to 5 millimetres wide, the median septum appears and the median lobe of the cardinal process becomes the most prominent part of the process. The shells have thus entered the neanic stage of their growth. The dorsal valve gradually becomes concave, and spines appear in the New Zealand species when the specimen is about five millimetres wide.

Hence *Leptalosia* is not a valid genus, but is the nepionic growth form probably of various Strophalosiid genera. The nepionic growth form differs in several important details from the mature Strophalosiid, and may conveniently be referred to as the "Leptalosia" growth stage. In this stage, the shell is adherent by the ventral valve over the umbonal part, or most of the viscernal disc. The dorsal valve is non-spinose, and more or less convex, the cardinal process bifid from a ventral aspect, and the median septum undeveloped.

RELATIONSHIP TO GENUS *Etheridgina* OEHLERT

Prendergast (1943) and, with reservations, Coleman (1958) have placed *Leptalosia* in synonomy with *Etheridgina,* which was proposed by Oehlert (1887) for *Productus complectens* Etheridge (1876), a tiny adnate shell clinging to crinoid stems. Tiny teeth and a hinge area were reported in the type species by Greger (1920). In proposing *Leptalosia,* Dunbar and Condra made no mention of Greger's observations, and considered that the cardinal process of *Leptalosia* differed significantly from that of *P. complectens.* However, Prendergast (1943) was convinced that the two were synonomous, pointing out that Greger had reported teeth and hinge area in specimens sent to him from Fifeshire. Prendergast (1943, p. 53) apparently confirmed these observations from some cotypes, and described the muscle scars as non-dendritic (*sic*). Prendergast also accepted Greger's reference to *Etheridgina* of some small American Strophalosiids that adhere by most of the ventral valve. To explain the difference in the cardinal processes stressed by Dunbar and Condra, Prendergast suggested (without foundation) that the description of the cardinal process in *Leptalosia* might have been generalized from Devonian species of a different stock, and that the American Carboniferous species might have a cardinal process similar to that of *P. complectens.*

Otherwise Prendergast (1943) and Greger (1920) seem to have ignored the internal details of *P. complectens.* However, the internal details of *P. complectens* are clearly productiform, as may be seen from the illustrations by Etheridge (1876). In the type specimens, examined at the Geological Survey of Scotland, Edinburgh, the cardinal process differs considerably from that of nepionic or mature *Strophalosia.* It is squat, massive, and bilobed from a ventral aspect, with a deep median cleft, and is four-lobed from the dorsal aspect. In front are two short septa, separated by a wide depression, and converging anteriorly to unite in front with a low median septum. On each side of the median septum is a large productiform (dendritic) muscle scar with scalloped edges. No Strophalosiid teeth or hinge-area were seen in the figured type specimens. *P. complectens* is probably a young productoid growth-form as suggested by Douville (1909, p. 157, footnote).

The only so-called Strophalosiid with a cardinal process and muscle scars somewhat like those of *Etheridgina* is *Limbella* Stehli (1954). But *Limbella* is closely related to *Aulosteges* and *Taeniothaerus*, and is not like *Strophalosia*.

By contrast, the species referred to *Etheridgina* from America by Greger (1920) and from Australia by Prendergast (1943) and Coleman (1958) are clearly Strophalosiid. In most of these species the cardinal process is usually trifid from a ventral aspect, with a prominent median lobe, the septum is single and median, the muscle scars rounded; teeth and cardinal areas are well developed, all characteristic features of true Strophalosiids at a neanic stage of development.

ACKNOWLEDGEMENTS

The New Zealand *Strophalosia* were studied at the Sedgwick Museum, Cambridge, during the tenure of an 1851 Royal Exhibition Scholarship. The writer gratefully acknowledges the facilities granted at the Geological Survey of Scotland for examining the types of *P. complectens*.

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A ONE-DIMENSIONAL FOURIER INVESTIGATION OF A SOIL MONTMORILLONITE

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(Received for publication, 15 December 1958)

Summary

A Fourier investigation of a glycerol-solvated soil montmorillonite, derived from olivine basalt, has been carried out. The investigation showed that the calculated formula $[K_{.16}\ Na_{.02}\ H_{1.00}]\ [Si_{6.36}\ Al_{1.64}]\ [Al_{.82}\ Fe^{3+}_{2.30}\ Fe^{2+}_{.08}\ Mg_{.48}\ Ti_{.08}]\ O_{18.36}\ (OH)_{5.64}$ was essentially the correct formula for the dehydrated mineral. In an electron density map of the mineral, partial resolution of the O-H and C-H planes of ions of the glycerol molecule was achieved. It was not possible to resolve the densities of the octahedral cations from those of the adjacent plane of oxygen-hydroxyl ions nor those of the tetrahedral cations from those of the adjacent plane of oxygen ions.

INTRODUCTION

A greenish-coloured montmorillonite appeared to be the only crystalline mineral present in the medium and fine clay fractions of a soil developed from olivine basalt near Waipiata, New Zealand (Soil Bureau No. 6335). Like many soil montmorillonites, the Mg-saturated, glycerol-solvated sample gave an intense 00*l* diffraction maximum, but, unlike most soil montmorillonites, seven other basal orders were distinguishable. A reproduction of an X-ray diffraction pattern obtained with Cu Kα radiation and a Mg-saturated, glycerol-solvated sample in which the basal planes were preferentially oriented is shown in Fig. 1.

EXPERIMENTAL

Soil from the A horizon was treated with H_2O_2 to remove organic matter, the free iron oxides were removed by the method of Aguilera and Jackson (1953), and the remaining mineral matter was dispersed in Na_2CO_3 at pH 10·5 after 10 minutes boiling in 2% Na_2CO_3. In order to reduce both crystalline and non-crystalline impurities as much as possible, only the medium clay fraction (0·2 to 0·08μ) was collected and used in the analysis. The fraction was washed free of sodium ions and kept in suspension.

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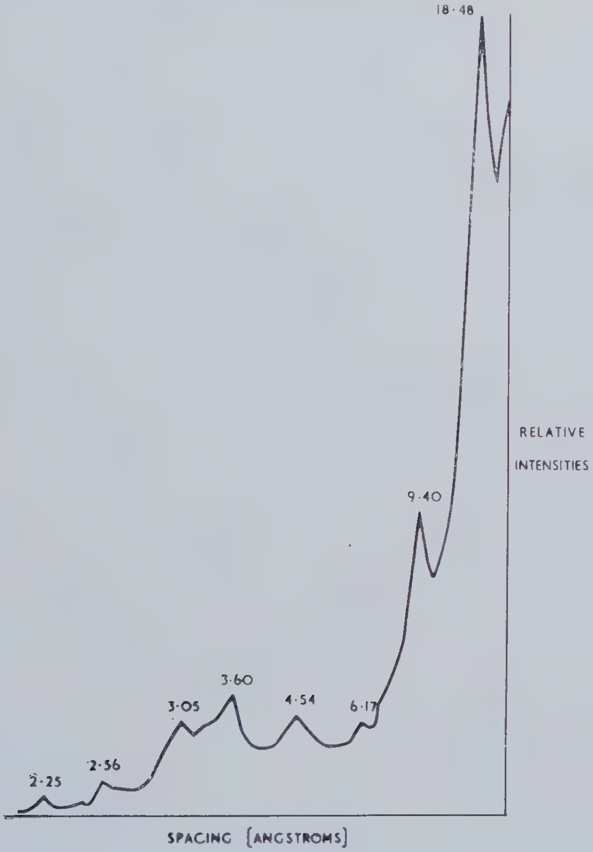

FIG. 1.—X-ray diffraction pattern of the montmorillonite.

Cation exchange measurements, heating-weight loss studies, and a chemical analysis for the nine major oxides were carried out. The results are recorded in Table 1. A chemical formula for the dehydrated mineral (i.e., no interlayer water) was calculated from these results. This formula showed that the cations in the octahedral positions were predominantly iron, and the mineral can be classified as nontronite. The formula was: $[K_{.16}\ Na_{.02}\ H_{1\cdot 00}]\ [Si_{6\cdot 36}\ Al_{1\cdot 64}]\ [Al_{.82}\ Fe^{3+}{}_{2\cdot 30}\ Fe^{2+}{}_{.08}\ Mg_{.48}\ Ti_{.08}]\ O_{18\cdot 36}\ (OH)_{5\cdot 64}$. For X-ray diffraction analysis, a sample was Mg-saturated and suspended in water over a glass slide in a tall beaker. Sufficient glycerol was added to solvate the interlayer surfaces of the sample, and the suspension was allowed to settle and dry down at room temperature. This slow sedimentation and drying produced a sample with a high degree of orientation of the basal planes. Even better orientation than this was obtainable when the sample was prepared by Kintner and Diamond's technique (1956).

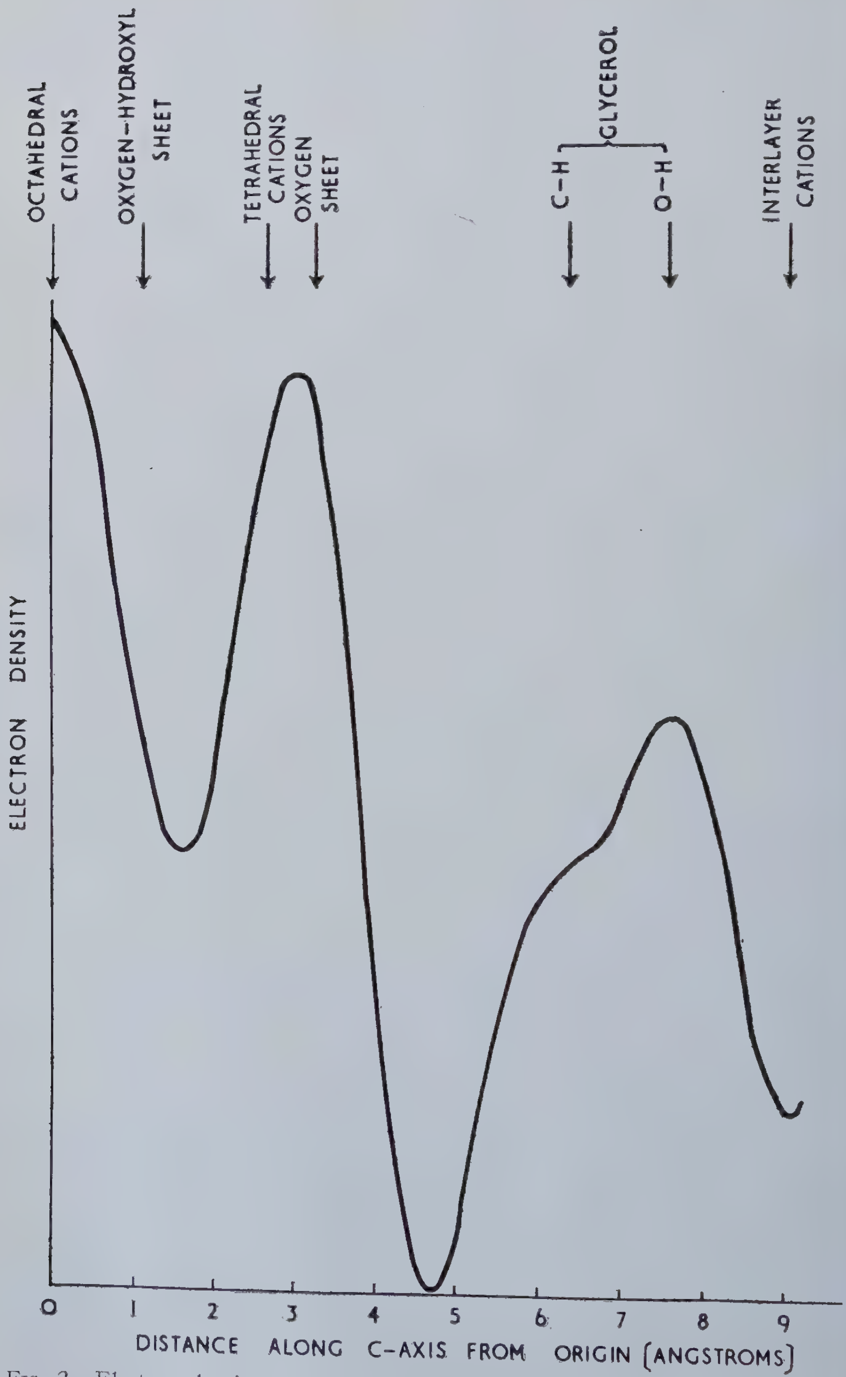

Fig. 2.—Electron density map of the montmorillonite showing partial resolution of glycerol molecule.

TABLE 1.—Analytical Data for Montmorillonite from Soil No. 6335A ($0{\cdot}2 - 0{\cdot}08\mu$)

	%		%
SiO_2	45·75	CaO	0·00
Al_2O_3	14·86	K_2O	1·03
Fe_2O_3	21·81	Na_2O	0·08
FeO	0·69	H_2O (110°-350°)	5·07
TiO_2	0·73	H_2O (350°-500°)	2·67
MgO	2·26	H_2O (500°-900°)	4·45

C.E.C. 129 meq per 100g

The intensities of the 00l diffraction maxima were obtained with a Philips X-ray diffractometer equipped with a Geiger counter spectrophotometer which was oscillated over the various maxima at a rate of 1° of 2θ per minute. Ten replicates were made for the 001 diffraction maximum, 8 for the 002, and 6 each for 003, 004, 005, 006, 007, and 008. The average intensity for each was then obtained by graphical integration. Intensities were converted into relative structure amplitudes by correcting them for Lorenz-polarization effects. Basally-oriented samples are more similar to single crystals than they are to randomly oriented powders in their diffraction effects, and the Lorenz-polarization correction for single crystals

$$\left(F^2_{00l} \propto I_{00l} \times \frac{\sin 2\theta_{00l}}{1 + \cos^2 2\theta_{00l}}\right),$$

where F_{00l} are the relative structure amplitudes ($l = 1, 2, 3, 4, 5, 6$), I_{00l} are the intensities of the 00l diffraction maxima and θ is the angle of reflection, was used in this conversion. The relative intensities and

TABLE 2.—X-Ray and Structure Data for the Montmorillonite.

Diffraction maximum	Average spacing (calc) Angstroms	Average spacing (obs) Angstroms	Relative intensities (obs)	Relative str. amplitudes (obs)	$\lvert F_{obs} \rvert$	F_{calc}
001	18·16	18·48	259	33	74	+ 84
002	9·08	9·40	72	25	56	+ 46
003	6·05	6·17	5	8	18	— 20
004	4·54	4·54	27	22	49	— 41
005	3·63	3·60	46	33	74	+ 76
006	3·03	3·05	24	26	58	+ 53
007	2·59	2·56	6	14	31	+ 37
008	2·27	2·25	4	13	29	— 28
					$\Sigma F^2 = 21{,}891$	$\Sigma F^2 = 21{,}879$

relative structure amplitudes obtained are recorded in columns 4 and 5 of Table 2.

The "true" 001 spacing was obtained by calculation from the *d*-values for the eighteen 004, 005, and 006 diffraction maxima. The "true" spacings for the higher orders were then obtained by dividing the "true" 001 spacing by the appropriate integer. This procedure was adopted in order to reduce the errors caused by the effects of the instrument upon the profiles of the diffraction maxima. The calculated and observed spacings are recorded in columns 2 and 3 of Table 2.

CALCULATION OF STRUCTURE FACTORS

Structure factors were calculated for a trial structure with the chemical formula: $[K_{.16}\ Mg_{.50}]\ [C_3H_5\ (OH)_3]_{3\cdot 2}\ [Si_{6\cdot 36}\ Al_{1\cdot 64}]\ [Al_{.82}\ Fe_{2\cdot 30}\ Fe_{.08}\ Mg_{.48}\ Ti_{.08}]\ O_{18\cdot 36}\ (OH)_{5\cdot 64}$. The projection of this unit cell upon the *c* axis has a centre of symmetry at 180°. The mathematical equation $F_{00l} = \Sigma f_n \cos l\phi_n$ was therefore used in the calculations, and the summation was carried out only over the region 0 to 180°. In this equation:

F_{00l} = the structure factor for the *l*th order ($l = 1, 2, 3, 4, 5, 6$)

f_n = the atomic or ionic scattering factor for the nth element in the material

ϕ_n = the angular measure of the intercept of the projection of the nth element upon the *c* axis, where $c = 18\cdot 16A = 360°$ angular measure, and the origin is taken in the centre of the plane of octahedral cations.

The various atomic and ionic scattering factors required were obtained from tables given by Bragg and West (1928) and by James and Brindley (1931). These, although not the best values now obtainable, were considered satisfactory for this purpose. No figures for the intercepts of the atomic and ionic planes with the *c* axis were available for this type of montmorillonite. The values used were obtained as follows:—

(1) It was assumed that the distances in Angstroms between the octrahedral sheet of ions (the origin) and the oxygen-hydroxyl sheet, the tetrahedral plane of ions, and the oxygen sheet were the same as in the muscovite investigated by Jackson and West (1930). The angular measure of the intercepts for these planes of ions were then obtained by multiplying the figures given in the last column of table 2 in Jackson and West's paper by the proportionality factor

$$\frac{\text{C montmorillonite}}{\text{C muscovite}} = \frac{18\cdot 16}{20\cdot 04}$$

(2) The interlayer cations were assumed to occur exactly in the centre of the cell, i.e., their intercept equals 180° angular measure.

(3) The intercepts for the hydroxyl plane and the C-H plane of the glycerol molecules were obtained by measurement from the electron density distributions given by Brown (1950) in his Fourier analysis of glycerol-solvated Wyoming bentonite.

The distances finally arrived at are given both in Angstroms and in angular measure in Table 3, together with the composite scattering factors, i.e., the combined atomic or ionic scattering factors for all the elements in each plane of atoms or ions.

From these data the structure factors were obtained. They are recorded in the seventh column of Table 2. They may be compared directly with the figures in the sixth column of the table which represent the structure amplitudes $|F_{observed}|$ scaled up so that $\Sigma F^2_{observed} = \Sigma F^2_{calc}$. The agreement between the two columns is very satisfactory, and the reliability index

$$r = \frac{\Sigma(|F_{ob}| - |F_{calc}|)}{\Sigma |F_{ob}|} = 0{\cdot}11$$

which, athough not a good guide when only eight reflections were taken, still indicates that the trial structure is, essentially, the true structure of the mineral.

In Fig. 2, a map of the electron density distribution along the *c* axis is shown. The map was obtained using the structure amplitudes $|F_{obs}|$ and the phases from the calculated structure factors. The summations were obtained by the use of Beevers-Lipson strips. The three regions of high electron density are due to the octahedral cations and their adjacent oxygen-hydroxyl plane of ions, the tetrahedral cations and their oxygen plane of ions, and the glycerol molecule. Had more orders been available it is probable that the region of high electron density due to the octahedral cations and adjacent oxygen-hydroxyl plane of ions would have been resolved into its two constituent peaks. As it is, partial resolution of the O-H and C-H planes of the glycerol molecules has been achieved.

ACKNOWLEDGEMENT

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TABLE 3.—Composition of Atomic Planes, Intercept Distances, and Composite Scattering Factors for the Trial Structure.

Plane of ions	Composition per ½ unit cell	Intercept distances from origin		Composite scattering factors							
		Angstroms	Degrees	001	002	003	004	005	006	007	008
Octahedral	$Al_{.41}$ $Fe_{1.15}$ $Fe_{.04}$ $Mg_{.24}$ $Ti_{.04}$	0·	0·	38·0	37·0	35·2	33·1	31·2	29·4	27·7	26·3
Oxygen-hydroxyl	$O_4\,(OH)_2$	1·12	22·1	57·0	53·4	50·4	46·8	42·6	39·6	35·4	31·8
Tetrahedral	$Si_{3.18}$ $Al_{.82}$	2·70	53·5	49·1	47·0	45·5	43·7	41·9	40·3	38·7	36·7
Oxygen	O_6	3·28	65·1	57·0	53·4	50·4	46·8	42·6	39·6	35·4	31·8
C-H of glycerol	$S_{1.8}$ H_8	6·40	127·0	26·9	25·4	23·6	21·6	19·2	17·3	15·4	13·4
O-H of glycerol	$(OH)_{4.8}$	7·60	150·8	45·6	42·7	40·3	37·4	34·0	31·6	28·3	25·4
Interlayer cations	$K_{.01}$ $Mg_{.25}$	9·08	180·0	4·1	4·1	4·0	3·8	3·6	3·4	3·3	3·1

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ON SOME OFFSHORE SEISMIC REFRACTION PROFILES IN THE COOK STRAIT, TASMAN BAY, AND GOLDEN BAY AREAS OF NEW ZEALAND

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(Submitted for publication, 15 November 1954. Received by Editor, 1 December 1958)

Summary

Marine seismic profiles show that the thickness of unconsolidated sediments varies from a few hundred feet in the Cook Strait to Golden Bay areas to 2,300 ft in the vicinity of Marlborough Sounds. The Tertiary geosynclinal sediments of N.W. Nelson thicken northwards beneath Golden Bay. The maximum recorded velocities are consistent with the basement rock mapped in neighbouring land areas.

INTRODUCTION

During the summer of 1953-54 the author had the opportunity to be in New Zealand on a Fulbright Research Fellowship and to be able to work with the scientists of the Geophysics Division, D.S.I.R. Largely through the efforts of Dr E. I. Robertson Director of the Geophysics Division, and the co-operation of the New Zealand Naval Board, a programme in marine geophysics was carried out. The purpose of this programme was both to add, however slightly, to the general geophysical and geological knowledge of New Zealand and to enable the exchange of information on offshore seismic techniques for future geophysical investigations and for research and development in the allied field of underwater sound transmission. The original intention was to map the seaward extension of the large Tertiary basin that covers the south-west portion of the North Island. However, due to poor weather during the period the ships were available, it was not possible to work in this area; a smaller scale investigation was carried out in the relatively sheltered area of Golden Bay, Tasman Bay, and the northern Sounds area of the South Island. These results did bring out some interesting features and are reported briefly here.

EQUIPMENT AND TECHNIQUES

Two ships took part in the operation. The larger ship, H.M.N.Z.F.A. *Isa Lei* served as the receiving ship. The recording gear was a truck-mounted 24-channel seismic exploration equipment, which was placed in the forward hold of the ship. A geophone and a hydrophone, suitably

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sealed, were placed on the bottom as the detecting elements. In deep water the hydrophone was suspended on a long cable and floated away from the ship so that during the reception of the shot the hydrophone and cable system was neutrally buoyant beneath the surface or slowly sinking. The smaller ship, SML 3355B, a converted HDML attached to the survey ship *Lachlan*, served as the shooting ship. The shots were fired electrically from a long cable off the stern of the SML and transmitted by radio and recorded on the photographic record of the receiving equipment. Distances were determined from the time of arrival of the water wave.

GEOPHYSICAL INTERPRETATION

The locations of the several refraction profiles are shown in Fig. 1. Profiles A, B, C, and D all showed a simple structure of a layer identified as the unconsolidated sediment, the velocity in which is only slightly greater than that in water, overlying a high velocity basement. Profile B was made from Okepuka Bay out through Tory Channel. Profiles A and C from Makara to Mana Island, and Profile D north of Queen Charlotte Sound. Profile E consisted of two legs nearly at right-angles. Velocities along the north-east leg indicated unconsolidated sediment overlying a layer of velocity 13,900 ft/sec. in turn overlying a basement of velocity 19,200 ft/sec. On the south-east leg the 13,900 ft/sec layer is much thicker; and the basement, if present at all, was not indicated.

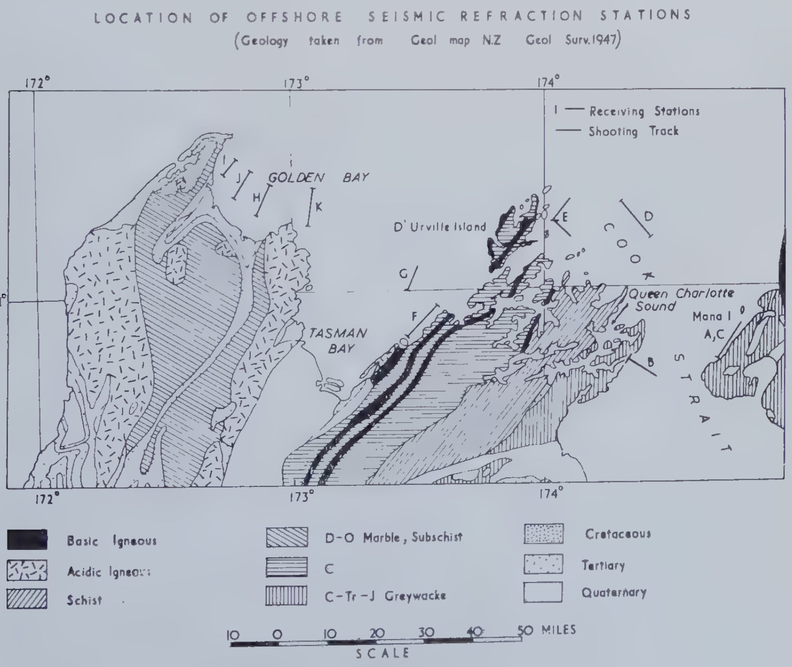

FIG. 1

Profile F showed a complicated structure. The reversed profile (i.e. shooting north-eastwards) revealed a 10,700 ft/sec layer beneath the unconsolidated sediment and a displaced 15,600 ft/sec basement toward the north; shooting south-eastwards showed only the 15,600 ft/sec basement. The profile is interpreted as indicating that the 10,700 ft/sec layer pinches out toward the north with a possible fault present. Profile G was shot in Tasman Bay and had to be terminated due to inclement weather after measuring a layer of intermediate velocity below the unconsolidated sediment. Profiles H, I, and J were all made in Golden Bay and showed unconsolidated sediment overlying two sedimentary layers, with velocities in the neighbourhood of 8000 ft/sec and 11,000 to 12,000 ft/sec, respectively, overlying a high velocity basement. Profile K was made off Separation Point. Shooting south indicated a section similar to that from the Golden Bay stations. Shooting north gave less detailed results but these indicated a maximum thickness for the sedimentary layers.

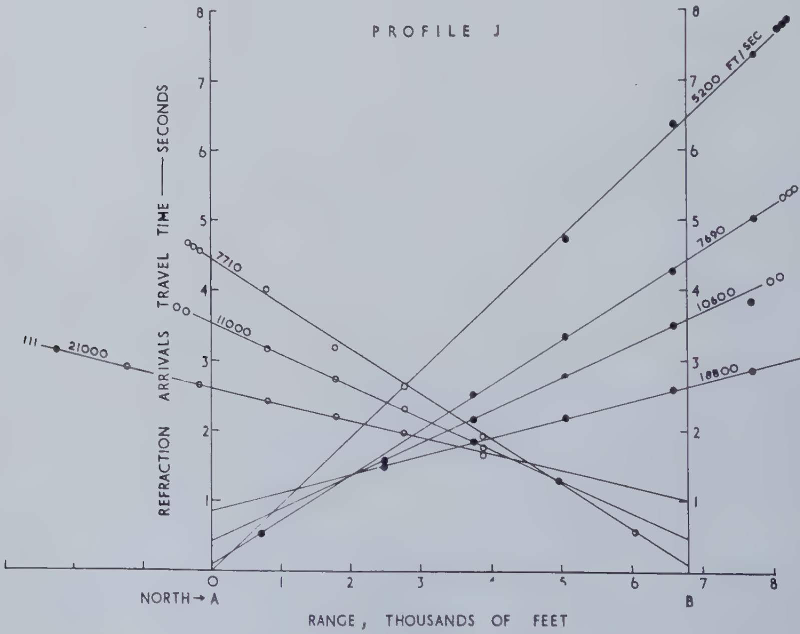

Fig. 2.

A sample travel time graph for one of the more complex stations is shown in Fig. 2. The abscissa is the range as determined from the travel time of the sound wave in the water channel. (A) is the location of the receiving ship for the northwards shooting and (B) the location for the southwards shooting. The ordinate is the travel time for the refraction arrivals, and the plotted points are the observed refractions from the various sub-bottom layers. The numbers on the refraction lines are the apparent velocities along the north- and south-shooting lines.

GEOPHYSICAL AND GEOLOGICAL RESULTS

A summary of the thicknesses and seismic velocities along each profile is shown in Fig. 3. Three features are of interest.

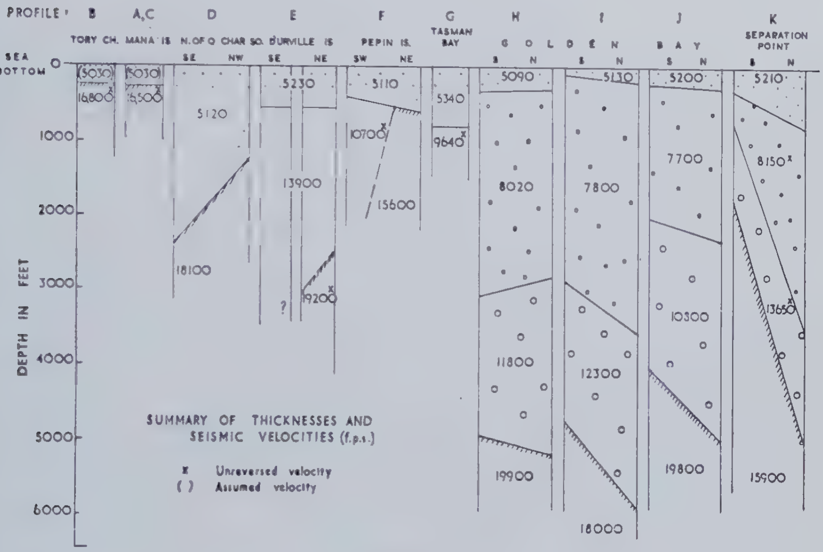

FIG. 3.

(1) *Thickness of unconsolidated sediment.* On the two profiles, B and A, C, near land in the Cook Strait area the unconsolidated sediment is thin, being only 250 ft thick. Similarly, on the profiles in Golden Bay, I, J, H, and K(S), the sediment is again thin, being 100 to 300 ft in thickness. Off Pepin and D'Urville Islands the thickness of sediment is 500 ft, increasing to 800 ft in Tasman Bay (Profiles G and K(N)). The thickest unconsolidated sediment, 1200 to 2300 ft, is measured on the most exposed profile, D, north of the Sounds area. All show the same pattern of thicker sediment away from the land areas.

(2) *Synclinal sediments in Golden Bay.* The geologic map of New Zealand shows that the southern shore of Golden Bay traverses a tertiary geosyncline which includes a Miocene mudstone more than 1000 ft thick underlain by an Oligocene limestone. The Golden Bay profiles measure the seaward extension of this syncline. Two sedimentary layers were observed, the contact between the two seismic layers probably corresponding to that between the mudstone and limestone. All four profiles, I, J, H, and K shows the synclinal sediments thickening toward the north, with maximum thicknesses of the order of 5000 ft.

(3) *Basement velocities.* The several profiles were made over widly differing basement types. It is interesting to compare the seismic velocities with rock types. Higher seismic velocities will be measured in the less compressible rocks. For sedimentary rocks the velocity increases progressively through the sequence, compaction, lithification, metamorphism. For igneous rocks the velocity is higher in the basic rocks than in the acidic rocks. In general the velocity is higher in the basic igneous and metamorphosed rocks than in the acidic igneous and sedimentary rocks. It is not unreasonable to identify the basement rocks at each profile by extension of the neighbouring land geology (Fig. 1). If this is done, then the basement under A, C, and B is greywacke and that under D schist. The upper layer of E is the Maitai-Te Anau limestone, mudstone, sandstone group; and the lower layer can be identified only with the ultrabasic to basic plutonic-volcanic sequences associated with the Maitai-Te Anau. Te upper layer of F is difficult to identify but may be granite; the lower basement is the Maitai-Te Anau. The basement under K is granite. For the Golden Bay area the basement under H and J is marble and that under I the subschistose core of the syncline. Table 1 is a comparison of rock type and seismic velocity. It shows the expected gradation. The ultrabasic to basics and the marble have the highest velocities of 19,000 to 20,000 ft/sec, the schist and subschist next with 18,000 ft/sec, then the greywacke with 16,500 ft/sec, the limestone, mudstone, sandstone with 14,000 to 15,500 ft/sec and the granites with 16,000 ft/sec and possibly lower.

TABLE 1.—Correlations of Seismic Velocities with Assumed Rock Types.

Basement Type (Nos from N.Z. Geol. map 1947)	Rock Description	Seismic Velocity
3	peridotites, serpentines, basaltic lavas	E 19,200 ft/sec
7	marble	H 19,900, J 19,800
7	subschistose conglomerates, breccia, greywacke	I 18,000
6	schist	D 18,100
9A	greywacke	B 16,800, AC 16,500
8	limestone, mudstone, sandstone	F 15,600, E 13,900
2	biotite granites	K 15,900, F 10,700

ACKNOWLEDGEMENTS

The author wishes to thank Dr E. I. Robertson and the New Zealand Naval Board for their considerable help in making the expedition possible and to those at the Geophysics Division and the Dominion Physical Laboratory who assisted in the operations. Particular appreciation is due to those who took part in the expedition, Dr Robertson, Messrs W. I. Reilly, F. E. Studt, Jenkins, R. A. Wooding, Burr, and Kusabs and to the personnel of the *Isa Lei* and the *SML 3355B*.

PAPAROA MINE AREA, GREYMOUTH COALFIELD: SWELLING PROPERTIES AND RESERVES OF COAL

By R. P. Suggate, New Zealand Geological Survey, Department of Scientific and Industrial Research, Christchurch

(Received for publication, 23 March 1959)

Summary

Coals in the Paparoa Mine area have dry ash-free volatile contents ranging from 16% to 30%. Swelling properties are related primarily to voltaile content. The reserves of coal are considered in two groups, that of consistently exceptionally high-swelling coal with volatile contents over 21% (swelling numbers of 9+ to 9+++) and that of inconsistently-high to low-swelling coal with volatile contents less than 21% (swelling numbers of 1 to 9). Reserves of the former, from all nearby areas regardless of access problems, amount to 480,000 tons of measured and 425,000 tons of indicated recoverable coal. Reserves of the latter amount to 125,000 tons of measured and 620,000 tons of indicated coal. Inferred reserves, entirely of consistently exceptionally high-swelling coal, amount to 1,800,000 tons, but much costly prospecting is essential to prove or disprove these reserves. Although the extreme north-east of the Mount Davy Block, which contains inferred recoverable reserves of 10 million tons of exceptionally high-swelling coal, is close to the south-east of the Paparoa Mine area, mining access would be most convenient from the west, and the 150,000 tons of indicated coal on its eastern margin are not incorporated in the estimates for the Paparoa area.

INTRODUCTION

Paparoa Mine has produced medium and low-volatile bituminous coal from two seams, the volatile content differing systematically from seam to seam and laterally within seams. As is to be expected with New Zealand coals of these ranks, the swelling properties vary from exceptionally high to almost nil, showing a first-order relation to the volatile content. Although Gage (1952) recognized rank variation in the Paparoa Mine area, he did not record the existence of low-swelling coal, and accordingly a review of the reserves of the Paparoa Mine area in terms of swelling properties of the coal is desirable.

Paparoa Mine lies on the eastern slopes of the Paparoa Range, two miles north of Mount Davy (Fig. 1), and two miles to the west on the western slopes of the range Liverpool Mine produces highly-swelling high-volatile bituminous coal; no coal has been mined from the crestal area of the range. Between the two mines the structure is complex, but to the south-west of Paparoa Mine and the south-east of Liverpool Mine the northern end of a major area of good structure—the Mount Davy Block—may contain workable coal. Mining access to this area would be most conveniently obtained from the Liverpool side, but if the Paparoa mine workings were to be extended into the eastern margin of the Mount Davy Block, valuable knowledge of the extents of the seams would be gained. For the purpose of this account, however, the Paparoa Area is considered to exclude the Mount Davy Block.

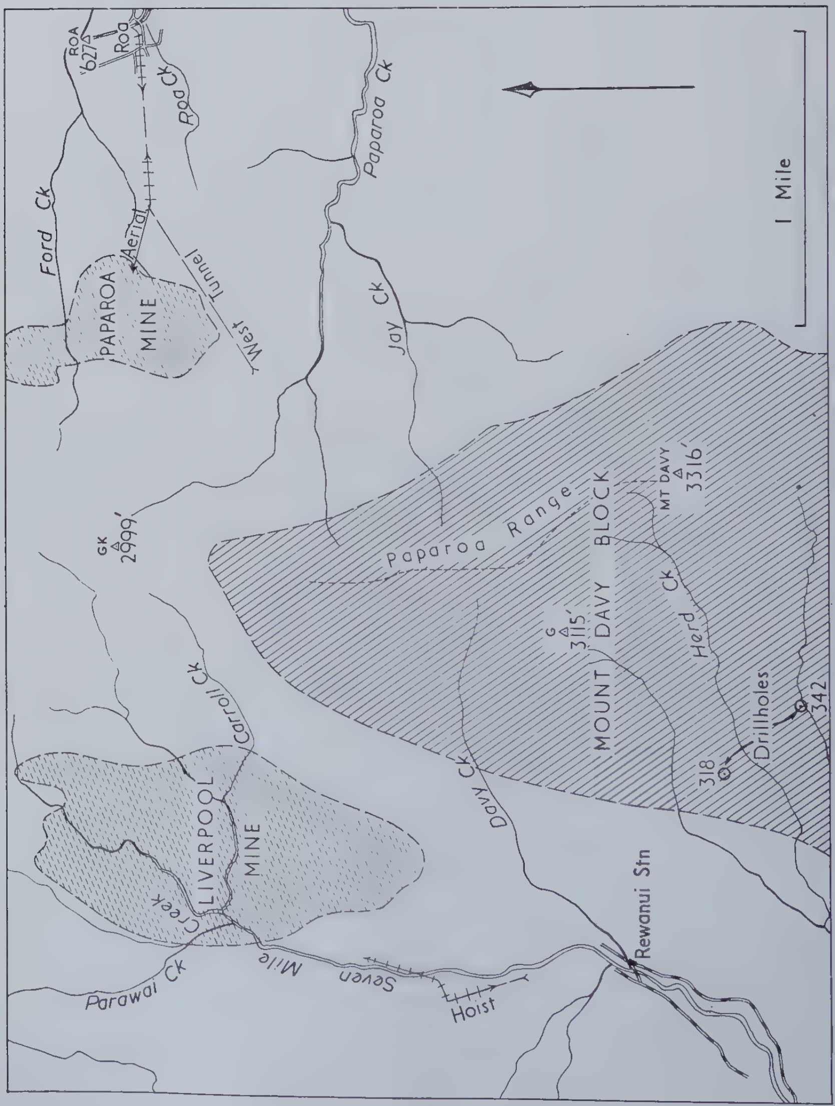

FIG. 1.—Map showing the area of Liverpool and Paparoa Mine workings in relation to the unworked coal measures of Mount Davy Block.

In calculating the estimates of recoverable coal, the criteria of Gage (1952) have been adopted, but in conformity with more recent practice, the terms "measured", "indicated" and "inferred" replace Gage's terms "proved", "probable" and "hypothetical", to indicate degrees of probability of existence of the reserves. Briefly, "measured" reserves lie in existing developed workings and extend therefrom for 1½ chains into unworked coal; "indicated" reserves lie in undeveloped coal, to a distance from known coal depending on an assumed rate of thinning of 1 ft in 2 chains; and "inferred" reserves are based solely upon a general knowledge of seam distribution and thickness variation. It follows that whereas production forecasts can be based on measured coal, and development can be initially planned on a basis of indicated coal, any figure of inferred coal is little more than a guess that gives an indication of what might be proved or disproved by prospecting.

Many prospective areas near Paparoa Mine would be costly to reach, but this account is concerned to draw attention to all areas, so that a comprehensive view can be taken. Any major increase in the output per shift would require a change in the outside haulage, at present a combination of aerial ropeway and endless-rope incline haulage. The 1957 production, from a single shift per day, was 21,872 tons, but the haulage was not worked to capacity.

STRATIGRAPHY AND COAL SEAMS

The following is the sequence in the Paparoa Mine area:—

Rewanui Formation	100 ft coal measures, including Upper Rewanui Coal Horizon
	c 400 ft coal measures
	No. 3 Seam
	100 ft coal measures
	No. 2 Seam (Lower Rewanui Coal Horizon)
Waiomo Formation	150 ft siltstone
Morgan Formation	No. 1 Seam (Morgan Coal Horizon)
	c 100 ft coal measures
	Lower Morgan Seam

The main workings are in No. 1 and No. 2 seams, and the present production comes entirely from the Aerial Section in No. 1 Seam (M 69). The Lower Morgan Seam may have been worked in the Paparoa Old Aerial Mine (M 12A) between the Middle Flat and the portal of the Aerial Section, but the seam correlation is uncertain. No. 3 Seam, worked in a small area near the west portal of the West Tunnel, has been prospected on the surface above the West Section No. 2 Seam workings (M 70), which themselves lie above the No. 1 Seam Aerial Section. No Upper Rewanui seam has been worked.

FACTORS AFFECTING THE SWELLING PROPERTIES OF PAPAROA COAL

The crucible swelling test is unstatisfactory for the highest-swelling New Zealand coals, and arbitrary designations of 9+, 9++, and 9+++ have been given at the Coal Section of the Dominion Laboratory to indicate progressively increased swelling beyond the 1 to 9 range of the test (Elphick, 1952). The general relations of swelling number to analysis have been discussed by Suggate (1959), who made a detailed study of the variations in the Paparoa Mine area. Besides a first-order relation between swelling number and volatile content in low-ash coals, second-order relations of swelling number to moisture and to thickness of cover were illustrated, these two factors being closely related. The discussion will not be repeated, but the first-order relation with volatile content is shown in Fig. 2, which also shows that coals with particularly high ash contents have diminished swelling numbers. Too few analyses of moderate and high-ash coals are available for a definite relation with ash content to be established.

Exceptionally high-swelling coals (those with swelling numbers of 9+ or greater) are almost solely those with over 21% volatiles, and few coals with volatile contents greater than 21% have swelling numbers of less than 9+. Thus, where areas of coal with over 21% volatiles are mined, the small quantities of coal with swelling number of less than 9+ are unlikely to reduce the exceptional swelling character of the greater part of the output. The reduction of swelling number by moisture in areas of thinner cover, appears to be confined to coals with less than 21% volatiles, and where such coals are mined, coal with inconsistently high (7-9), medium (4-6), or low (1-3) swelling numbers is likely to be produced, and the swelling number of the run-of-mine coal may be expected to vary considerably according to the particular sections being worked. Accordingly in the following discussion the reserves of coal are considered in two groups, those with more and those with less than 21% volatiles.

STRATIGRAPHIC VARIATION OF VOLATILE CONTENT

The dry ash-free volatile contents of coals in the Paparoa Mine area range from 30% to 16%, and depth-volatile relations for coals within and beyond this range, including some from the Paparoa Mine area, were discussed by Suggate (1956). Within Paparoa Mine, Nos 1 and 2 seams, separated by 150 ft of Waiomo Formation, differ in volatile content by between 1% and 2%, a more accurate estimate not being possible owing to the uneven distribution of samples within the seams. A decrease of 1% volatiles for each 100 ft increase of stratigraphic depth is assumed, such a relation being consistent with the conclusions of Suggate (1956).

LATERAL VARIATION OF VOLATILE CONTENT WITHIN SEAMS

Suggate (1959) illustrated the detailed variation of volatile content in the Aerial Section of Paparoa Mine, showing a general westward

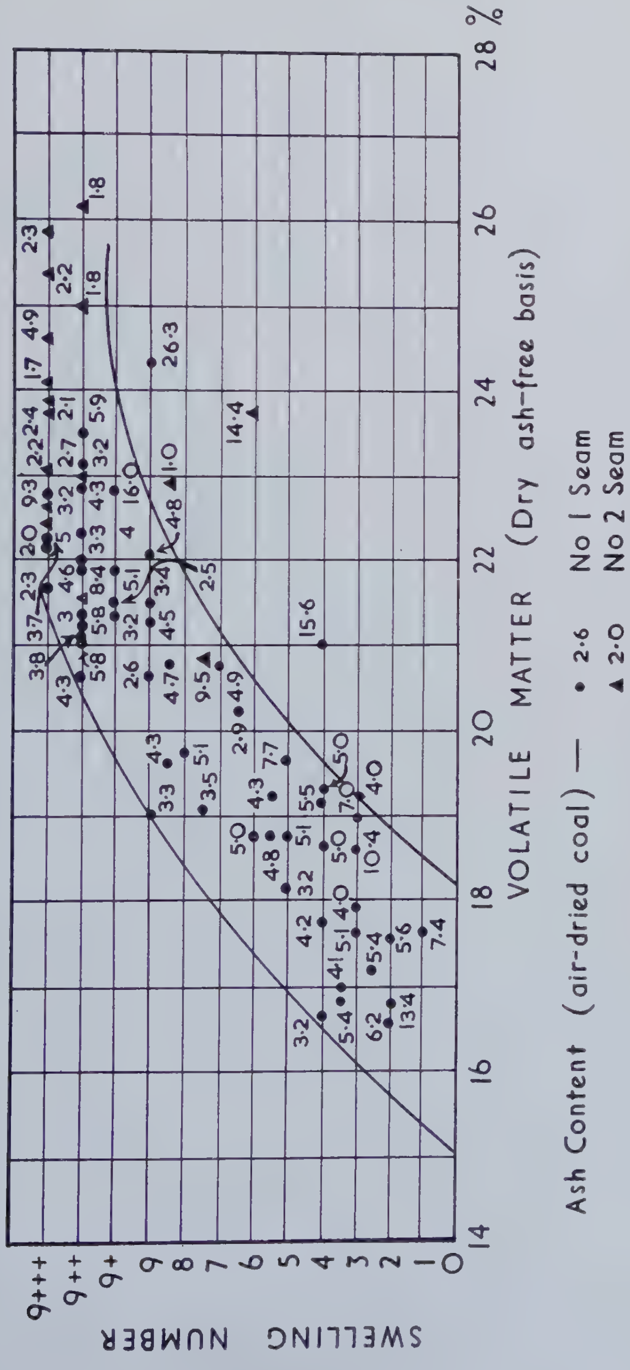

FIG. 2.—Relationship of swelling number to volatile matter for coals of both No. 1 and No. 2 Paparoa Mine seams. Ash content is also indicated.

increase and a minimum within the eastern workings. Broader variations within the Mount Davy Block to the south were shown for the same (Morgan) coal horizon by Suggate (1955), the same westward increase being clear, but the minimum along the eastern edge of the Block being largely inferred from the rank pattern of Wellman (1952). On the following maps showing areas of workable coal, the lines of equal volatile content (isovols) are shown to be following the general pattern, but comparatively few analyses are available outside the Paparoa Mine area.

RESERVES IN AREAS OF COAL WITH CONSISTENTLY EXCEPTIONALLY HIGH SWELLING NUMBER

The areas considered are those at present being developed, those developed but not pillared, and those undeveloped areas to north and south considered by Gage (1952) to contain indicated coal. For undeveloped areas, Gage's estimate area numbers are retained, these being shown on Figs 3 and 4. Some areas are divided by the 21% isovols, and are accordingly considered in two parts. The figures given are of recoverable coal.

Measured Coal

AERAL SECTION (NO. 1 SEAM) (M69). The whole of the Aerial Section, except the higher ground within the undeveloped area between the New Dip and the Old Dip workings, contains coal with over 21% volatiles. These workings and the area available for development are estimated to contain 350,000 tons of coal.

WEST SECTION (NO. 2 SEAM) (M70). This section, above the No. 1 Seam Aerial Section, was developed some years ago, partly pillared and then temporarily abandoned. Gage (1952) estimated it to contain 130,000 tons of coal.

Indicated Coal

The areas shown on Figs 3 and 4 are taken from Gage's maps, with some modifications resulting from the development of Paparoa Mine.

NORTH-WEST PART OF ESTIMATE AREA 4 (Fig. 3). This area lies to the west of the old No. 1 Seam workings (M13) that were developed from the West Tunnel. Gage (1952) considered that the seam would be workable westwards as far as a fault, but that it would thin to the south. Only the north-west part of this area contains coal with over 21% volatiles, the quantity being estimated at 100,000 tons.

NO. 3 SEAM: ESTIMATE AREA 49. Lying above the West Section No. 2 Seam (M70), this seam is not shown on the accompanying maps. Gage noted a persistent stone band within the seam, and an analysis shows an ash content of 12·7%. Nevertheless Gage's estimate of 175,000 tons of indicated coal is accepted, but trenching and sampling of the outcrops is desirable before development.

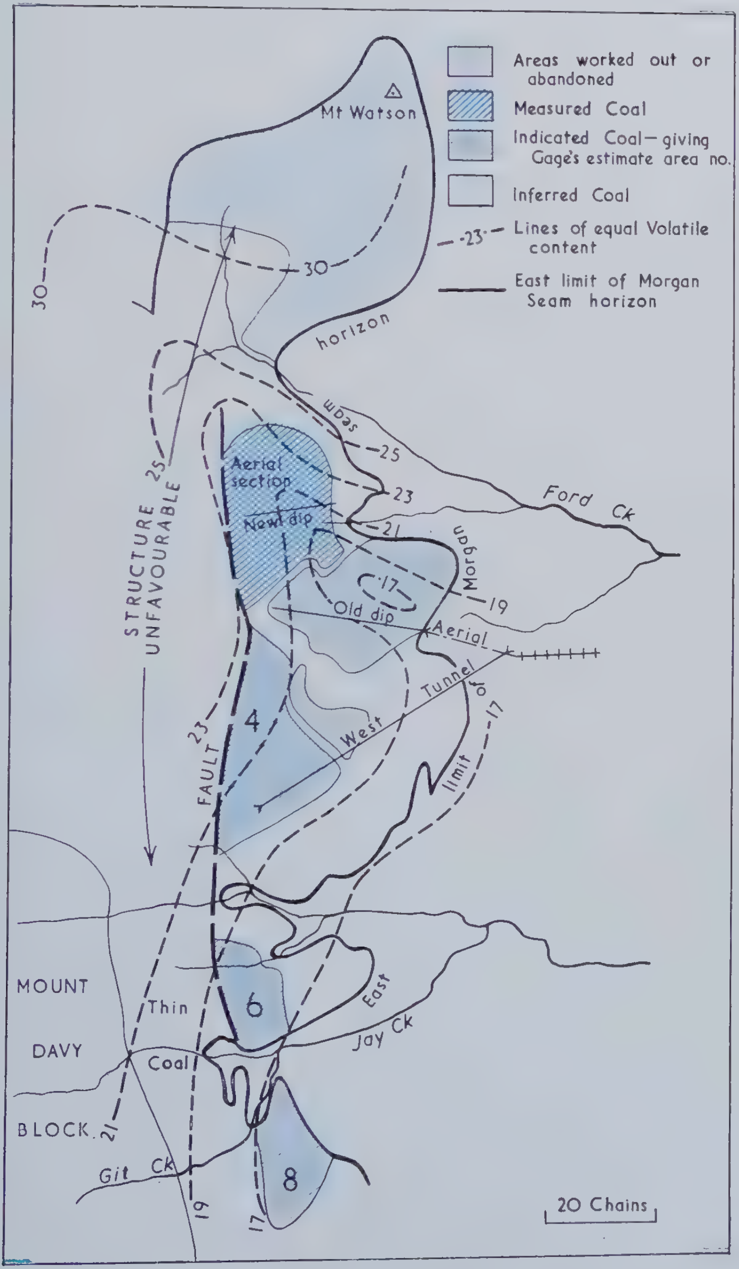

FIG. 3.—Paparoa Mine Area showing No. 1 (Morgan) seam horizon.

ESTIMATE AREA 18 (Fig. 4). This area lies to the south-west of the old No. 2 Seam workings (M16) developed from the West Tunnel. Gage expected the coal to thin to the south, and this was confirmed in recent prospecting from the tunnel. This necessitates a more conservative estimate, the figure of 160,000 tons being considerably smaller than that of Gage.

NORTH-WEST PART OF ESTIMATE AREA 19 (Fig. 4). This area lies half a mile south of the south-west portal of the West Tunnel, from which it is separated by the deep valley of Toms Creek. The north-west half of this estimate area contains coal with over 21% volatiles, estimated to amount to 90,000 tons.

Table 1 summarizes the estimates of measured and indicated coal with over 21% volatiles:—

TABLE 1.—Measured and Indicated Coal With Over 21% Volatiles.

Area	Measured	Indicated
No. 1 Seam, Aerial Section—developed and undeveloped	350,000	
No. 2 Seam, West Section	130,000	
Estimate Area 4 (N.W.)		100,000
Estimate Area 49 (No. 3 Seam)		175,000
Estimate Area 18		60,000
Estimate Area 19 (N.W.)		90,000
TOTALS	480,000	425,000

Inferred Coal

Apart from the Mount Davy Block, which is discussed below, inferred coal is confined to the Mount Watson area, to the north of the Aerial Section. This area was not prospected during the survey of Greymouth Coalfield, the results of which were published by Gage (1952), but on his maps Gage includes substantial areas of Nos 1 and 2 seams as inferred coal, although few outcrops are known. Accepting Gage's areas and a recoverable thickness of 6 ft of coal for each seam, an estimate of 1,800,000 tons of inferred recoverable coal is made for the two seams.

RESERVES IN AREAS OF COAL WITH INCONSISTENT SWELLING NUMBER

These areas lies east of the 21% isovols shown on Figs 3 and 4.

Measured Coal

This is confined to part of the Aerial Section No. 1 Seam (M69), in the upper levels of the New Dip and in the upper levels of the undeveloped area between the New Dip and the Old Dip workings; the quantity is 125,000 tons.

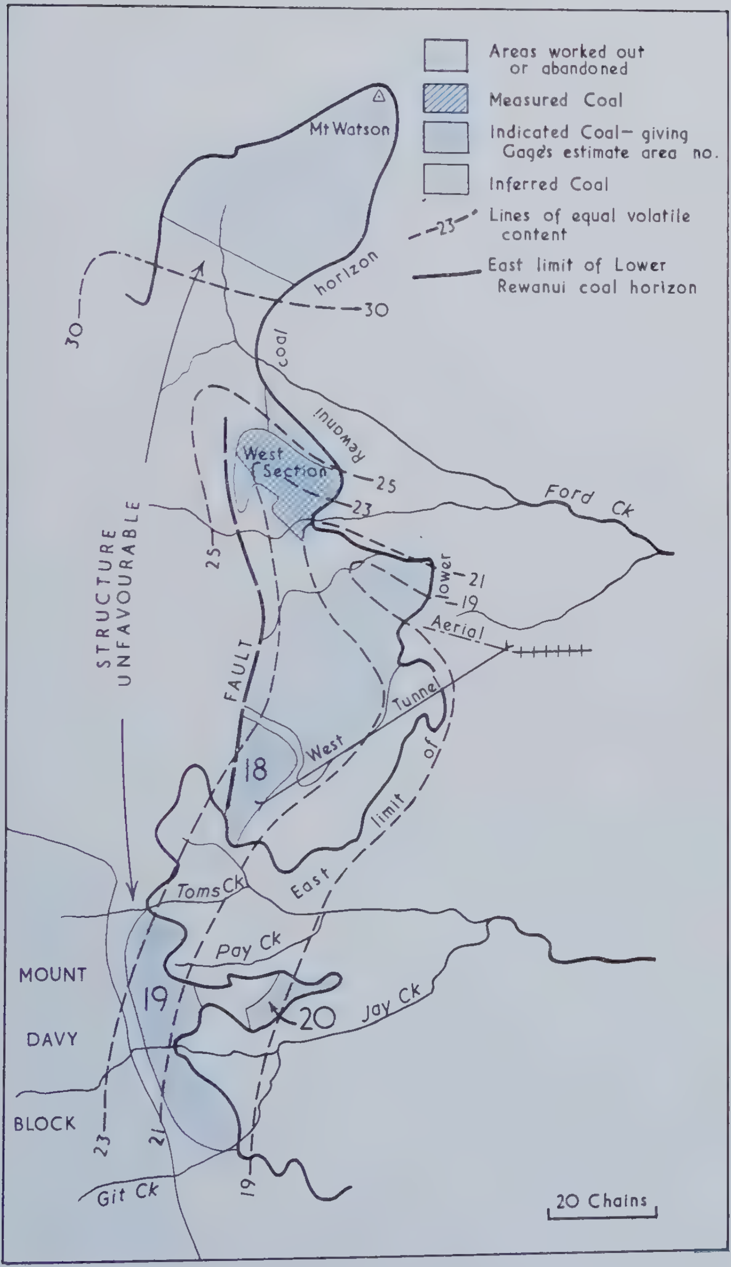

FIG. 4.—Paparoa Mine Area showing No. 2 (Lower Rewanui) seam horizon.

Indicated Coal

SOUTH-EAST PART OF ESTIMATE AREA 4 (Fig. 3). This area in No. 1 Seam, to the north-west of the West Tunnel and to the dip of the old workings of M13, is estimated to contain 150,000 tons. The north-west part of the estimate area, containing higher-volatile coal, has been discussed above.

ESTIMATE AREA 6 (Fig. 3). This area in No. 1 Seam, between Pay and Jay creeks, was estimated by Gage to contain 157,000 tons.

ESTIMATE AREA 8 (Fig. 3). This area in No. 1 Seam, to the south of Jay creek, was estimated by Gage to contain 85,000 tons.

SOUTH-EAST PART OF ESTIMATE AREA 19 (Fig. 4). This area of No. 2 Seam, from Toms Creek to Git Creek, is estimated to contain 100,000 tons. The north-west part of the area, containing coal with over 21% volatiles, has been discussed above.

ESTIMATE AREA 20 (Fig. 4). This area in No. 2 Seam, on the spur between Pay and Jay creeks, was estimated by Gage to contain 80,000 tons.

Table 2 summarizes the estimates of measured and indicated coal with less than 21% volatiles.

TABLE 2.—Measured and Indicated Coal With Less Than 21% Volatiles.

Area	Measured	Indicated
No. 1 Seam, Aerial Section—developed and undeveloped	125,000	
Estimate Area 4 (S.E.)		200,000
Estimate Area 6		155,000
Estimate Area 8		85,000
Estimate Area 19 (S.E.)		100,000
Estimate Area 20		80,000
TOTALS	125,000	620,000

THE MOUNT DAVY BLOCK

Estimate area 19 (Fig. 4) adjoins the north-east margin of the Mount Davy Block, from which it is separated by important faults. The block itself extends west for a mile and south for five miles, and its structure is considered to be substantially unbroken, with moderate dips to the south-west and west. Its coal seams within the Rewanui and Morgan formations contain coal with generally higher volatile contents (25 to 34) than those close to Paparoa Mine, and the swelling properties of low-ash coals are expected to be uniformly 9++ and 9+++. Drilling in the south end of the block proved no area of workable coal, despite the encouraging results of the first drillhole (266). In the north end of the block, west of Mt. Davy, although the Lower

Rewanui coal horizon contained seams of workable thickness, correlation from one drillhole to another was not possible (Suggate, 1955). Concluding that workable coal might extend in a series of overlapping lenses at this horizon north-eastwards to the thick seams of the Paparoa area, Suggate noted that this horizon could be reached at drillhole 318 by an easily-graded stone drive from Rewanui, 60 chains long. Workings would then be almost exclusively rise workings, far more attractive than dip workings from the Paparoa side. Nevertheless, should estimate area 19 be worked from Paparoa, underground prospecting could be undertaken into the Mount Davy Block. The southward extension of workable Lower Rewanui coal within the block is quite unknown, but the thinning-out of the seams in the eastern outcrops and the fairly thin seams in drillhole 342 may well imply that coal is confined to the extreme north. An estimate of 9 million tons of inferred recoverable coal from 1,000 acres is made for this area, assuming that only one Lower Rewanui seam is workable.

Additional reserves of about 150,000 tons indicated and 1,000,000 tons inferred are given for seams at the Upper Rewanui coal horizon on the eastern margin of the Mount Davy Block, where outcrops of thick coal are known half a mile south-east of the south-west portal of the West Tunnel of Paparoa Mine (Fig. 5). Access to these outcrops, which are at an elevation of 2,000 ft, would be most difficult from the Paparoa side, and little easier if Lower Rewanui seams were worked beneath them from the Rewanui side.

The drilling of the north end of the Mount Davy Block gave disappointing results in the Morgan Formation, but the Lower Morgan Seam is of workable thickness in both drillhole 318 and 342 and Suggate (1955) indicated some uncertainty that the high ash contents of the samples from this seam in both drillholes were due to inherent ash rather than to contamination. Nevertheless, this horizon is not promising on the east side of Mount Davy, and no estimate is justified. It may be noted that because of contamination of samples from many seams, the results of drilling in the Mount Davy Block were most difficult to assess, and only conservative estimates of quantities can be made even for the more promising Lower Rewanui seam horizon.

Beyond Greymouth Coalfield, low-sulphur coal with swelling number of 9+ or above, similar to that from the Mount Davy Block, may perhaps be found in the unprospected and inaccessible Pike River Coalfield (Wellman, 1949), 12 miles to the north of Mt. Davy on the crest of the Paparoa Range.

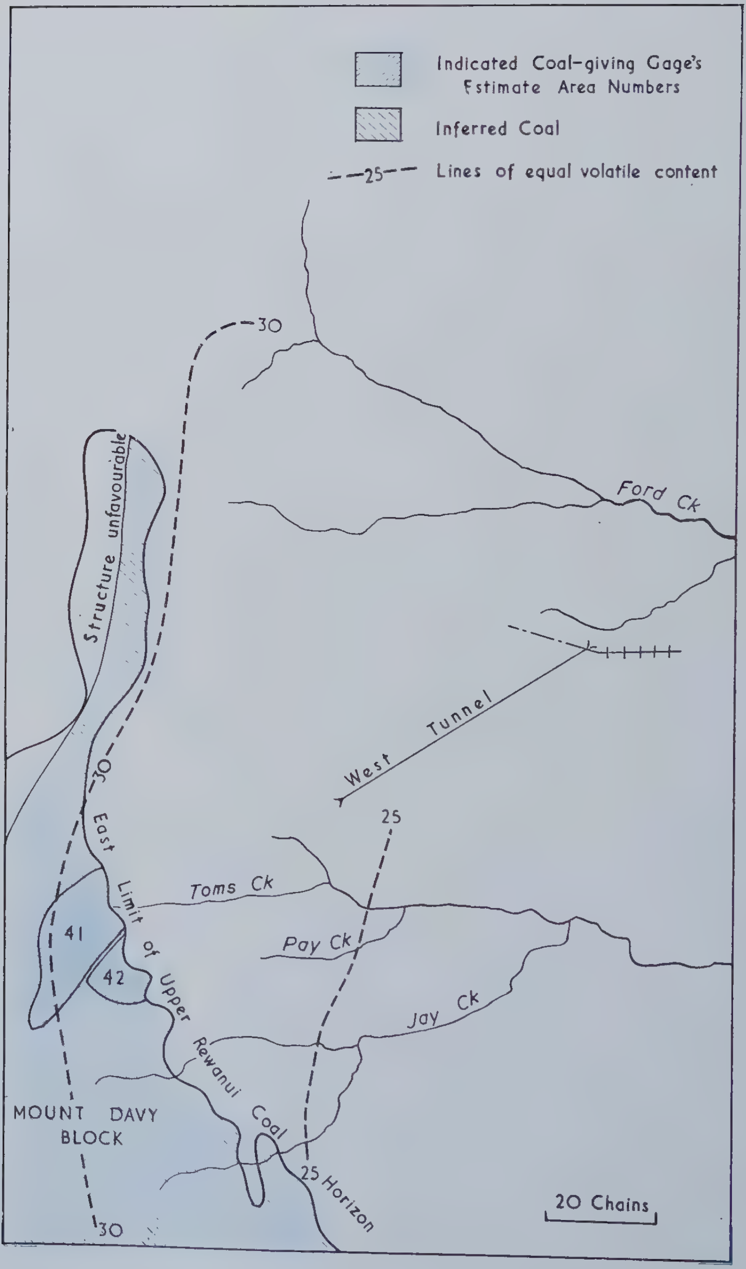
Indicated Coal–giving Gage's Estimate Area Numbers
Inferred Coal
25
Lines of equal volatile content
30
Structure unfavourable
Ford Ck
West Tunnel
30
East Limit of Upper Rewanui Coal Horizon
25
Toms Ck
Pay Ck
41
42
Jay Ck
MOUNT DAVY BLOCK
25
30
20 Chains

FIG. 5.—Paparoa Mine Area showing Upper Rewanui seam horizon.

ACKNOWLEDGEMENTS

The coal analyses on which this paper is largely based were made at the Coal Section of the Dominion Laboratory, Lower Hutt. The writer is indebted to Messrs. F. E. Bowen and W. A. Sara of the Geological Survey, Greymouth, for helpful comment on the text and for coal sampling in Paparoa Mine.

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SCHISTOSE ROCKS FROM ST. HELIERS BAY, AUCKLAND

By E. J. SEARLE, University of Auckland

(Received for publication, 8 December 1958)

Summary

Epidote amphibolites occurring as accidental blocks in the tuff of the St. Heliers Bay volcano and at Taylor's Hill, Auckland, are described. They are regarded as the product of the retrogressive metamorphism of a gabbroid intrusion into the basement rocks.

INTRODUCTION

Most of the rocks described in this article were collected from tuff deposits erupted from a volcano near St. Heliers Bay, east of the city of Auckland. Activity at this centre which is located on the coastline between Archilles Point and Karaka Bay (map reference: N42/886614 N.Z.M.S. 1), was largely abortive and ceased after a phreato-magmatic phase that ejected much tuff but produced neither a scoria cone nor lava flows. The tuff contains a notably large proportion of accidental material both as blocks and as finely comminuted debris; juvenile material is limited to fragments and blocks of vesicular and rather glassy olivine basalt that is usually crowded with small xenolithic inclusions. Since the eruption, marine erosion has driven back the sea cliffs and removed a large part of the volcanic edifice, whilst wave action has sorted the spoil and thrown back to the shore many of the larger and more resistant blocks, in this way forming a pocket boulder beach and spreading a veneer of boulders over the rock-cut platform. Some of the rocks to be described were collected from this naturally concentrated source whilst others, of identical types, were obtained directly from the tuffs. A few further samples of similar rocks were also found in the tuff accumulation surrounding Taylor's Hill (N42/387591), a small eruptive centre near at hand, but although a diligent search has been made at other, more remote centres in the Auckland volcanic field, none has as yet afforded rocks of comparable nature.

In describing the St. Heliers section of the Waitemata coast, Fox (1902) recorded the occurrence of "large blocks of Maitai slates, quartzites and phylites" in the tuff and, since some of the "Maitai blocks" were several feet in diameter, he inferred that the rocks *in situ*

N.Z. J. Geol. Geophys. 2 : 368-79.

from which they were derived must be located close by. Greywacke blocks of this size are now not apparent, and in fact, large blocks of rocks other than fine-grained basalt are rare. The tuff itself is composed of fragments predominantly derived from the mid-Tertiary grits, sandstones, and mudstones of the Waitemata Group, together with juvenile basaltic ejectamenta, whilst the majority of the beach boulders, which have been derived from the tuff and survived attrition, have proved to be mainly epidote amphibolites.

For the purposes of this investigation thin sections were cut from some eighty specimens and these were examined microscopically. Twelve of the sections proved to be of the greywacke type (argillites, greywacke-sandstones and volcanic wackes) and the remainder were metamorphic rocks that could be assigned to the albite-epidote-amphibolite facies.

The greywacke fragments encountered were typical epidotized and prehnitized sediments of Chl. 1-Chl. 2 grade, similar in kind to the greywackes found widely in North Auckland. In thin section the fine-grained varieties were semi-opaque, and almost isotropic under crossed nicols, and so were difficult to resolve mineralogically. But, generally, the thin sections of these rocks gave no indication of thermal metamorphism, or of regional metamorphism any more advanced than in rocks of similar types elsewhere. Likewise, blocks of Tertiary sediments incorporated in the tuff, in their mineral constitution, bore no impress of thermal or of dynamic change.

DESCRIPTION OF THE SCHISTS

(Numbers quoted refer to thin-sections in the petrological collection of the Department of Geology, University of Auckland.)

Of the schistose rocks examined in thin-section those occurring most frequently are albite-epidote-amphibole schists. Rocks of this type usually exhibit a well developed mineralogical foliation, with coarse layers of oriented amphibole porphyroblasts alternating with bands of leucocratic minerals. The majority are so strongly foliated that their schistose nature is obvious in the hand specimen. In some, the schistosity is on a fine scale, with the layers folded and puckered and crossed by strain-slip cleavage. In other rocks there is little evidence of crystalloblastic change, but the effects of cataclastic reduction are obvious. In all types, the schists have been broken by secondary planes of slip at an angle to the main schistosity, and along these minor shears vein minerals have often formed.

The amphibole, in rocks such as 5235 and 5261, is present in wide-bladed prophyroblasts (Fig. 1), and although this texture is most characteristic, other textural variations are quite common. For example, in rocks 5214, 5228, etc. the amphibole has adopted a nematoblastic habit (Fig. 2), and in 5223 it is distinctly lepidoblastic. The commonest

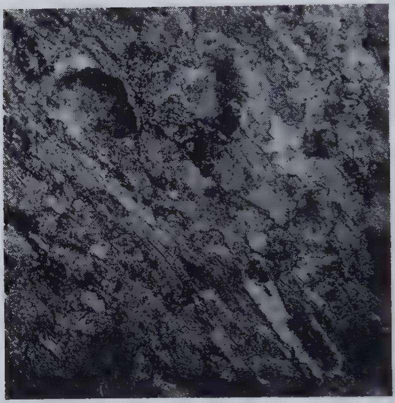

FIG. 1.—Typical epidote-amphibolite with coarse-bladed, blue-green actinolite and granular epidote. (Section No. 5249; × 45.)

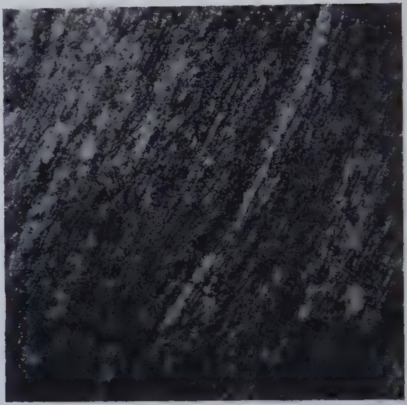

FIG. 2.—Finely foliated amphibolite; showing deeply pleochroic actinolite of nematoblastic habit in thin layers separated by leucocratic bands. (Section No. 5228; × 50.)

variety of amphibole is bluish green and deeply pleochroic, with the rather drab interference colours usual in actinolite rather than in hornblende, but varieties with interference tints normal to common hornblende are by no means uncommon. Both are found together in many sections, as, for example, in 5235 and 5247, where porphyroblasts of the more hornblendic species are extended in the direction of foliation by outgrowths of the actinolitic type. Particularly in those rocks in which the latter type of amphibole has the rod-like habit, e.g. 5238, there are "eyes" of amphibole with little body colour and bright interference tints between crossed nicols, which appear to represent rotated hornblende relics of the parent rock. Optical properties, other than birefringence, of the two types are not markedly different. In both, $2V_x$ varies between 68° and 84°, and $z \wedge c = 10° - 18°$. In the more pleochroic varieties the pleochroic formula is: X = yellow, Y = olive green, Z = blue-green.

Since it is not possible on optical properties alone to distinguish between aluminous and non-aluminous amphiboles, it is inadvisable on the criteria available to assert with confidence that there is any significant difference between the two types of amphibole noted above. Nevertheless, it would seem not unrealistic to regard the more abundant amphibole as actinolite, and to designate the more highly birefringent variety, occurring both crystalloblastically and as eyes and kernels, as at least in part common hornblende. This is more apparently the case in sections such as 5200 where actinolite, as above determined (Fig. 3), has formed outgrowths on crystals of augite and hornblende, both of which are clearly relics of the parent rock. If the amphibole which has been defined as actinolite is indeed that mineral, then the optical data suggest for it a composition close to ferrotremolite (Winchell, 1951, p. 433).

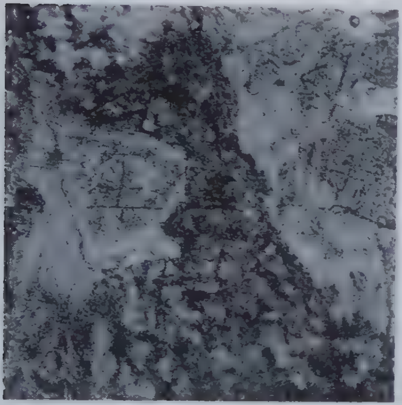

FIG. 3.—Relict of augite with rims of amphibole. (Section No. 5188; × 45.)

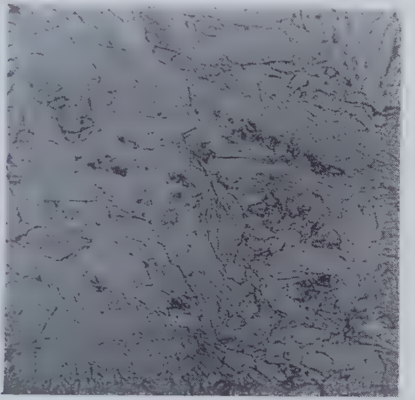

FIG. 4.—Tremolite schist. (Section No. 5200; × 45.)

A colourless bladed amphibole ($2V_x = 76° - 84°$; $z \wedge c = 16° - 18°$; $\beta = 1{\cdot}627 \pm {\cdot}002$), accepted as tremolite, occurs along with actinolite and in a few very strongly foliated rocks (e.g. 5222, 5188) is the only amphibole present and almost exclusively constitutes the rock (Fig. 4). Where it accompanies actinolite the textural relationship between the two indicates that tremolite has been the later in developing.

Epidote is present in almost every section examined and occurs in granular aggregates scattered throughout the rock, in strings or veins, and, more rarely, in large yellowish aggregates. Relict felspars which are found in a number of sections are so crowded with finely divided epidote as to be almost opaque in transmitted light and to have a silky white lustre when examined in reflected light. The granular epidote usually produces bright interference colours, and is optically negative with $2V_x = 72° - 76°$, which indicates that it is pistacitic in composition, with 20% to 30% of iron epidote (Winchell, 1951, 449). Many larger masses and some of the euhedral prisms found occasionally have anomalous extinction and are almost certainly zoisitic in composition. In a few cases (e.g. 5245, 5260), epidote minerals build up the bulk of the samples which may be fragments of massive veins of the rock *in situ* and may, therefore, be regarded as true epidosites. Euhedral prisms of epidote were also found enclosed by albite veins penetrating some of the amphibolite specimens.

Granular sphene in coarse aggregates is frequently rendered almost opaque by a witish secondary mineral considered to be leuxocene. It is generally subsidiary in amount to the epidote minerals but in a few instances is particularly abundant in the form wiry stringers parallel with the foliation and lying close to the amphibole-rich layers (Fig. 5).

Albite, present in the majority of sections studied, is found characteristically in the saussuritized ghosts of plagioclase and in clear outgrowths, with low refractive index, that border them (Fig. 6). It occurs, too, sometimes with quartz, in small veins that intersect the larger epidote aggregates (5222, 5262), and in many strongly foliated samples there are tiny irregular lakes of albite scattered through the sections. In the rock of section 5250 layers rich in albite alternate with those rich in actinolite.

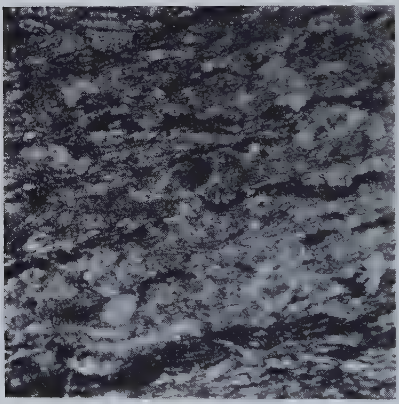

FIG. 5.—Albite-epidote-sphene-amphibolite in which coarse strings of sphene are parallel to the foliation. (Section No. 5190; × 45.)

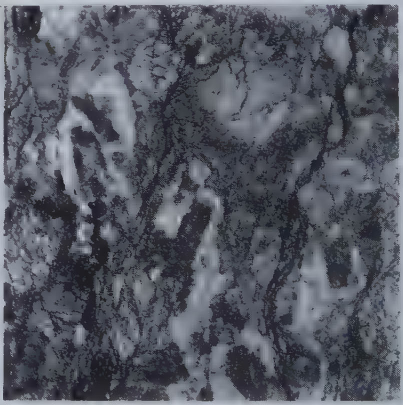

FIG. 6.—Albite-epidote-sphene-amphibolite with dark ghosts of saussuritized plagioclase rimmed with albite. (Section No. 5234; × 45.)

Of the ore minerals, pyrite is perhaps the most commonly occurring, but although magnetite was detected in fewer rocks, it is usually abundant when it is present. In 5223 the magnetite is euhedral and evenly distributed throughout the section; elsewhere (e.g. 5218) it is more granular and is associated more closely with the amphibole masses than with the other minerals of the rocks. Ilmenite was recorded in some of the sphene-rich rocks, and apatite is a rare accessory.

Chlorite is not an important constituent of any of the schists and where present is usually developed along minor shear planes; in a few instances it was detected in association with vein quartz.

Reference has already been made to relict feldspars. Albite twinning is apparent frequently, and extinction angles measured on the composition planes were invariably low. However, the feldspar has so obviously been leached of calcium during metamorphism that no significance can be attached to the values obtained as far as determining the composition of the original mineral is concerned. The coarse lath-like habit of many of these ghosts is reminiscent of the felted plagioclase in dolerites, whilst in a few other cases, the anhedral ghosts conform to an earlier granitic texture.

Relict pyroxenes are represented by augite (Fig. 7), diallage (Fig. 8) and, in one rock, by enstatite. In thin sections 5223 and 5189 the augite ($2V_z = 58°$; $z \wedge c = 40°$) is virtually unaltered and has merely suffered a measure of cataclastic disruption. In other cases it remains only as cores within amphibole aggregates.

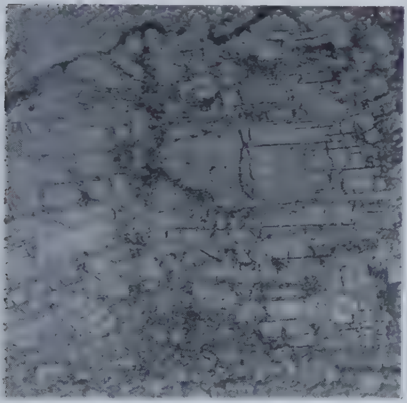

FIG. 7.—Relic of augite cataclastically deformed and disrupted. (Section No. 5208; × 45.)

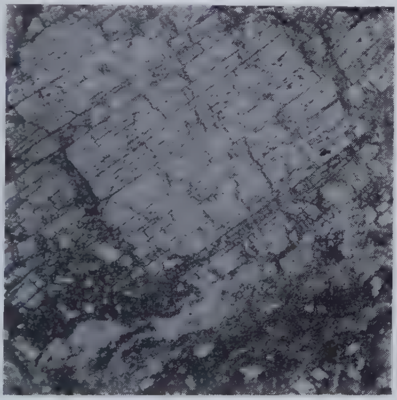

FIG. 8.—Large relic of diallage which has been partially fragmented by cataclastic reduction. (Section No. 5208; × 45.)

Among the vein minerals, prehnite ($2V_z = 64°$) is found in a majority of sections. Whilst it usually forms in thin veins, it also occurs sporadically in large masses which may represent wider parts of vein systems, and in euhedral prisms and aggregates within vein quartz. Calcite is rare, but was noted in irregular granoblastic masses along with prehnite, in sections 5210 and 5221; separate veins of calcite were not observed. Vein quartz is usually granoblastic in texture, but in a few cases, notably 5231 and 5233, it is columnar to fibrous, with the broad fibres arranged perpendicular to the walls of the veins.

Little foliation is apparent in the more cataclastically affected rocks. In the more extreme cases, shearing has reduced the whole rock to small disrupted and rotated fragments so that none of the original fabric has survived. But in other rocks altered mainly by re-crystallization sufficient of the original texture remains to point clearly to the parent material. Thus section 5233 is obviously gabbroic with plagioclase, augite, diallage, and enstatite developed in a coarse granitic texture. Gabbroic affiliations are shown also by sections 5220, 5239, and 5247, and, as already stated, the ghost feldspars of other rocks accord with a doleritic or gabbroid parentage.

Although a few of the blocks have lava adherent to them, the bulk are clean, angular fragments. This fact, coupled with the total absence from them of high-temperature metamorphic minerals, would suggest that few of them have had direct or prolonged contact with the magma body—a view which gains support from the nature of some fused xenoliths which do occur in basalt blocks in the tuffs. These fused inclusions have been so changed by the hot basaltic environment that they have been transformed into dense, near-isotropic bodies of buchite type that are mineralogically unresolvable. A small number, however, show a streakiness compatible with a former schistose texture, and a few have patches in which the characteristic cleavage pattern of the amphiboles is clearly discernable, and rare relics of amphibole. The deduction is that these particular xenoliths were schistose amphibolites prior to their immersion in the basaltic liquid.

For the accidental blocks, which show no fusion, metamorphism must have antedated the basaltic activity at the site. It follows that the schists must be representative of some component of the basement rock beneath the Waitemata sediments through which the volcanoes have burst. In this connection it is noteworthy that greywacke blocks are only minor constituents of the accidental materials in the tuff of these volcanoes. Such rocks are, indeed, very rarely found in the fragmental rocks associated with any of the large number of small volcanoes in the Auckland field. The following mineralogical assemblages were noted in the crystalloblastic rocks:—

(1) Albite—epidote—amphibole.

(2) Albite—epidote—sphene—amphibole. (a)—with minor chlorite.
(b)—with minor calcite.

(3) Albite—tremolite.

(4) Albite—epidote—tremolite.

(5) Albite—epidote.

(6) Quartz—epidote.

The cataclastically reduced rocks appear to be granulated gabbroic or doleritic pyroxenites.

DISCUSSION

While the schistose rocks provide evidence of a hitherto unsuspected element of the basement of the district, the existence there of a pre-Waitemata basic or ultrabasic intrusion will occasion no surpise, for in the Silverdale-Warkworth district, north of Auckland, such intrusive masses are well known to be numerous. In a serpentine body at Harper's Quarry, south of Wellsford, Bartrum (1948) has already described inclusions of a somewhat similar nature to the rocks described in this article. They include gabbros and amphibole schists. A few years earlier the same writer, Bartrum (1937), described in detail a much wider variety of plutonic and metamorphic rocks which occur as xenoliths in a group of andesite dykes at Whangarei Heads. Again, Turner and Bartrum (1929) recorded a diopside-hornblende-plagioclase-schist found, together with greywacke and dolerite, as inclusions in serpentinite south of Silverdale, barely twenty miles north of the present site. Bartrum (1935) also described a variety of schists from a Jurassic conglomerate at Uriroa Point, Kawhia, and Macdonald (1954) did likewise for a range of schists from conglomerates from a number of horizons in the Jurassic sequence at Kawhia.

Bartrum (1947) regarded the xenoliths that he had described as evidence of a metamorphic basement of considerable extent underlying the Auckland Province, and conjectured that it could be correlated with the Otago metamorphic terrain. With regard to the Whangarei xenoliths Bartrum (1937) came to the conclusion that, while some of the rocks had been affected by contact metamorphism, the general explanation demanded acceptance of an earlier series of calcareous sediments, with basic igneous rocks and tuffs, that had been invaded by batholithic masses of gabbroid rock during a period of severe regional stress, which must have concluded before the final consolidation of the magma. This view was supported by Allen (1951), but Turner (1937), in an appendix to Bartrum's paper, inclined to believe that these rocks were essentially the product of contact metamorphism.

This present record of metamorphic rocks from St. Heliers Bay raises again problems similar to those considered by Bartrum. Do they provide further evidence of a buried widespread metamorphic province in Auckland, or can they be explained more satisfactorily by some local metamorphic process?

The following considerations appear to have bearing on the assessment of the situation and the resolution of the questions involved:—

(1) No boulders or pebbles were found as such *in situ* in the tuff; all fragments were angular and sharp. It would seem to be most unlikely that they could have originated from a conglomerate bed in the Mesozoic basement or in the Tertiary cover. Again, although the rocks show some variation in texture and type, there is not the wide assort-

ment of rocks that is characteristic of the Jurassic conglomerates and neither do they resemble in any way the rocks of such Tertiary conglomerates as the Albany Conglomerate in the Waitemata Group.

(2) The Recent eruptions that brought the schists to the surface were of the phreato-magmatic type and the rocks were finally blasted out, not floated out in lava. The relative paucity of greywacke, as compared with schistose fragments, indicates that the metamorphic rocks were not buried deeply in the basement but, rather, that they formed a relatively superficial element of the sub-surface structure. The Tertiary cover apparently rests directly on the Mesozoic strata; it is probably no thicker than 1,000 ft to 1,500 ft, and may be very much thinner locally, for in neighbouring islands (Motutapu, Motuihe) the unconformable contact between the two is exposed at the surface. The greywackes themselves are known to be a very thick formation.

(3) The mineralogical assemblages shown by the rocks are quite consistent with a basic or ultrabasic igneous parentage. Intrusions of this sort into the pre-Waitemata strata are by no means uncommon in other localities, and those at Silverdale and at North Cape are considered by Bartrum (1934) to have been emplaced in early Tertiary times.

(4) There is good reason for believing that a major fault or downwarp, defining the boundary between the Manukau lowland and the Auckland Peninsula, is located not far south of the volcanoes at St. Heliers, and Marwick (1948) has suggested that the period of deformation and faulting involved was in the Miocene, and perhaps well back in that period.

(5) The mineral assemblages of the schists contain two distinct elements: the albite-epidote-actinolite association which suggests a relatively higher temperature equilibrium, and the ubiquitous prehnite and quartz veining which is probably conditioned by a low temperature environment. This dual mineralogy would appear to demand two episodes of metamorphic recrystallization in which two completely different sets of temperature and pressure conditions obtained.

(6) Attention has already been drawn to the total absence of high temperature—low pressure minerals as of the sanidinite assemblage, which would appear to discount any probability of metamorphism arising from contact with the Recent basaltic lavas. In addition, the xenoliths in the basalts show, through relict minerals and the clear imprint of schistose fabric, that the amphibolite schists antedate the basalt.

In the light of these facts, four possible hypoheses should be examined:—

(a) That the schists are representative of an Auckland pre-greywacke metamorphic terrain of wide extent and comparable with the Otago schists, as has been suggested by Bartrum (1937) for the schistose rocks he has described.

The writer can see little of merit in applying this hypothesis to the present case. The supposed metamorphic basement is recognized from xenolithic fragments in peculiar metamorphic environments and from the presence of metamorphic rocks in Jurassic conglomerates. But the xenoliths are not markedly related to the pebbles in the conglomerates and may be explained (as Turner has done for those at Whangarei) in an entirely different fashion. In the present instance, the absence of more numerous fragments of graywacke, which the phreatic explosions may reasonably have been expected to have brought up, if the schists were derived from lower in the basement sequence, seems to preclude acceptance of the theory. Nor can it reasonably be imagined that an explosive eruption would originate from the necessary depth to carry sub-greywacke material through the massive Mesozoic sequence, let alone that it should do so without bringing to the surface preponderant quantities of the more superficial greywacke materials. And lastly, the difference between the accidental blocks and their xenolithic equivalents in basaltic blocks, shows that the former were not carried up in magma prior to their explosive eruption to the surface.

(b) That the schists represent tuffaceous beds from the greywacke sequence metamorphosed by contact with an intrusive mass (c.f. Turner's (1937) suggestion for xenoliths at Whangarei Heads). Presumably in the Auckland case, this would imply metamorphism by the magmatic body that gave rise to the volcanoes. The absence of typical high temperature minerals, even from blocks with adherent lava, seems to weigh heavily against the explanation. Its merit lies in the possibility of a shallow metamorphic aureole about a basic intrusion, with a thin carapace of schistose rocks, fragments of which could be carried through the Waitemata cover by the blast of gas explosion. But the lack of typical contact rocks stands in the way of acceptance of this picture.

(c) That the schists may, perhaps, be derived from a basic or ultrabasic intrusion in the Mesozoic sediments that was metamorphosed along with them, but, being more amenable to metamorphic change, permitted alteration to a mineral assemblage more advanced than that of the enclosing sediments. Hutton (1940, p. 69) argues that basic igneous material would typically provide "albite-epidote-chlorite-rock, with actinolitic amphibole, sphene and aberrant relics of augite" in the Chl. 1 subzone near the Chl. 2 isograd. In the region studied by him, basic rocks in subzones Chl.2 and Chl. 3 are now represented by albite-epidote-chlorite-schists, sometimes with plentiful sphene, but actinolite is lacking. In the rocks of the highest metamorphic grade in the region he found green schists, "some with chlorite alone, or with actinolite in addition to chlorite, but except for one unusual type, never with actinolite alone".

On theoretical grounds it would appear that schists such as those at St. Heliers, in which actinolite is so abundant, and chlorite so unimportant a constituent, would not likely be formed from basic igneous sources, involved in metamorphism which has merely transformed enclosing sediments into schists of Chl. 1-2 grade. If it is correct that common hornblende is present with the actinolite, so that the assemblage approaches that of the epidote-amphibolite rather than that of the green schist facies, then there would be even greater incongruity.

It may be argued further, that pre-Cretaceous basic intrusions are relatively unknown, although other suitable source rocks, such as basic volcanic wackes are available. However, the relict texture and mineralogy clearly indicates a gabbroid or doleritic parentage, and as such intrusions as are known in the region are post-Cretaceous in age, it is reasonable to infer that the parent intrusions are of the same age. On both grounds, the concept of the schists being produced by metamorphism which at the same time scarcely affected the greywackes seems to be unacceptable.

(d) That the schists were developed by retrogressive metamorphism of a post-Cretaceous basic or ultrabasic intrusion in response to dynamic stress in early Tertiary times, and during the phase of falling temperatures following intrusion.

This hypothesis is that preferred by the present writer. Such a mass could well provide unstable mineral assemblages, sensitive to adjustment under stress that was insufficient to provoke marked changes in the enclosing greywacke. It is essential to invoke stress to explain the clear cataclastic effects which characterize many of the samples. This explanation virtually amounts to the retrograde metamorphism of a high grade assemblage, and from such either an epidote amphibolite or a green schist would be an expectable product, according to the temperature of the intrusion when stress became operative.

The extensive prehnitization, which is typical of the rocks could be explained by late hydrothermal action, or by very low grade metamorphism after temperature had fallen considerably, and probably when conditions of tension rather than of stress obtained. It may well be that, during this phase, the materials for mineralization were largely allogenic, and that the prehnite and silica in the veins originated in calcic, aluminous or silicic solutions carried in from the sedimentary country rock, which could readily provide them.

ACKNOWLEDGEMENT

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OCCURRENCE OF IGNIMBRITE IN THE SHAG VALLEY, NORTH-EAST OTAGO

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Summary

Petrography of the acid igneous rock of the Shag Valley in North-east Otago, previously classified as a quartz porphyry, indicates that this rock is an ignimbrite. Formerly described as a dyke, the Shag Valley rock is now considered to be a surface rock interbedded with coal measures of Upper Senonian age, and is the first occurrence of ignimbrite described from the South Island of New Zealand.

Introduction

In reading the petrographic description of the "quartz porphyry" from the Shag Valley, North-east Otago (Benson, 1946), one of the authors (A.S.) noticed that the description closely corresponds to that of an ignimbrite. The late Professor Benson's thin sections, from the University of Otago collection, were kindly made available to Steiner by Professor D. S. Coombs. A re-examination of these has confirmed the correctness of Benson's description but not his classification. Subsequent field work suggests that it is a surface rock and not a dyke.

Previous Work

The Shag Valley acid igneous rock was first observed and mapped as a dyke by McKay (1887a, b), who called it a felsite.

On the basis of a petrographic examination, Paterson (1941) classified the rock as a quartz porphyry. He considered it to be a vertical dyke of post-Senonian age, and because there were no known acid igneous rocks in the Dunedin olivine basalt-phonolite-trachyte association,* nor any likelihood of a genetic relationship with this association, he thought that it was intruded prior to these Upper Tertiary volcanics.

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*Professor Coombs and Dr A. J. R. White have recently re-examined a pumiceous tuff within the Late Tertiary volcanic sequence of Waikouaiti, first recorded by Park (1904) as the Waikouaiti Leaf-bed Series, containing "numerous inclusions of grey pumice". The pumice contains 73% SiO_2 calculated on a water-free basis.

N.Z. J. Geol. Geophys. 2 : 380-4.

With slight modification, Benson (1946) accepted both Paterson's classification of the rock as a quartz porphyry and Paterson's opinion that it is a dyke, although he stated (p. 6): "It has not been possible to observe the contact of the porphyry with the formations which it invades". Benson assumed a petrogenetic relationship between the "quartz porphyry" and the Oligocene basaltic rocks of North-east Otago and concluded that "an Oligocene age . . . seems the most probable, though it has not yet been proved to be correct".

OCCURRENCE AND AGE

Field examination shows that, far from being a continuous series of outcrops, as might be expected from earlier investigations, the "quartz porphyry" occurs as a series of isolated and generally widely separated exposures not at all compatible with the dyke hypothesis. Its outcrops are confined to an infaulted strip of coal measure conglomerates (Shag Point Group) lying between two major sub-parallel faults of the Waihemo Fault Complex. On the north-east side, the coal measures are faulted against greywackes and semi-schists (Chl. 1 and 2 subzones) of the Horse Range and on the south-west side against glauconitic sandstones of Upper Cretaceous and Lower Tertiary age. Benson (1946, p. 4) also noted a "strip of deeply-weathered high-grade schist [Chl. 3 on Turner's (1938) classification]" occurring on the pine-covered ridge 250 yards north of the Horse Range road (S146/352243). This he appeared to regard as evidence for the occurrence of a third fault, between and sub-parallel to the main fractures, and along which the "dyke" was intruded. A close examination of the ridge mentioned does not support the contention that an inlier of Chl. 3 occurs here in contact with the "quartz porphyry". Certainly, large blocks of schist do occur, but they do not appear to be in place and are more probably a portion of the coarse phase of the basal fanglomerate of the coal measures.

At the most northerly outcrop of the "quartz porphyry" (S 146/343254), the rock is clearly seen, at the south-west end of the hill, to lie on an uneven gently dipping surface of coal-measure conglomerates. A distinct megascopic planar flow structure, due to the parallel arrangement of flaky xenoliths and biotite plates, is here quite regular and sub-parallel to the bedding of the coal measures. The attitude of this structure (Strike 330° Dip 25° NE) is also consistent with the north-west trend of the "dyke" and with the general strike of the coal measures shown on Benson's map, though from Benson's account he evidently did not visit the northern outcrop. At the north-eastern end of the same hill, coal measures are, at least stratigraphically, above the igneous rock. The "quartz porphyry" is thus considered to be interbedded with the coal measures which, at Shag Point, contain fossils of Upper Senonian age. High angles of dip of the planar structure (up to 80°) were mentioned by Benson (p. 6), who considered the structure to be the result of laminar flow; such high dips do not negate the present hypothesis, since the same author recorded dips of 70° and 55° in the coal measures.

PETROGRAPHY AND PETROCHEMISTRY

Under the microscope, the Shag Valley acid igneous rock exhibits a distinct vitroclastic or shard texture which is present in all Benson's and Paterson's thin sections as well as in three sections (P 22174 A, B, C) cut from samples collected by the present writers. Moreover, in sections cut perpendicular to the planar structure, the shards as well as the phenocrysts of biotite and feldspar exhibit a considerable degree of parallelism; such a parallelism is a common characteristic of ignimbrites. The Shag Valley acid igneous rock is thus considered to be an ignimbrite. This is the first occurrence of ignimbrite described from the South Island of New Zealand.

Neither the shard texture nor the parallelism of shards and phenocrysts was recognized by Paterson. However, Benson noted the presence of some shards exhibiting "bogen" structure and stated (p. 13) that "the glassy matrix in this rock is abnormal", but he did not comment on any implications of the shard texture or on the abnormality of the groundmass. On the other hand, the mineralogical data given by both Benson and Paterson provide all the essential information concerning the mineralogical composition of the rock.

It should be noted that chemically as well as petrographically the Shag Valley ignimbrite resembles some of the ignimbrites of the North Island. When the two analyses of the Shag Valley rock (Benson, 1946, Table II, Nos 11, 12) are compared with the average of 16 analyses of North Island ignimbrites (Table 1 of this paper), it is seen that the most important difference is the lower soda and the higher potash content of the Shag Valley ignimbrite. This difference is reflected in the higher ratio of orthoclase to albite as seen in the norm, and also by the presence of potash feldspar in the Shag Valley rock as contrasted with its usual absence in the North Island ignimbrites. The other differences, shown up by the norms and the Niggli values, are chiefly due to this difference in feldspar. For instance, the comparatively high percentage of normative quartz (and high qz. value) in the Shag Valley rock is accounted for by the higher weight percentage of silica in albite.

PETROGENESIS

The new evidence rules out any association of the Shag Valley ignimbrite with the Oligocene basaltic lavas of the North-east Otago province as postulated by Benson (1946). Moreover, the Shag Valley rock falls outside the area of the low-temperature trough in the SiO_2-$NaAlSiO_4$-$KAlSiO_4$ diagram (Benson, Fig. 4, p. 22). Thus, its composition is not readily compatible with an origin by fractional crystallization of basaltic magma. Since the North Island ignimbrites also lie outside the low-temperature trough (Benson, 1941), it is probable that the Shag Valley ignimbrite originated from a syntectic magma of rhyolitic composition, in a similar manner to the ignimbrites and rhyolites of the Taupo volcanic association (Steiner, 1958).

TABLE 1.

	1	2	3
SiO_2	70·99	75·48	73·11
Al_2O_3	12·47	12·18	13·37
Fe_2O_3	0·85	0·63	1·20
FeO	0·31	0·25	0·82
MgO	0·56	0·34	0·35
CaO	1·33	0·28	1·64
Na_2O	1·21	0·51	3·61
K_2O	5·40	5·88	3·70
H_2O+	3·77	2·63	1·20
H_2O-	2·54	1·48	0·43
TiO_2	0·30	0·26	0·26
P_2O_5	0·06	0·06	0·07
ZrO_2	0·02	0·02	—
S	0·03	0·03	—
MnO	Tr	0·01	0·06
BaO	0·35	0·06	0·08
Sr	0·02	0·01	—
	100·21	100·11	99·90

NORMS*

	1	2	3
Q	43·25	51·09	35·51
or	33·30	36·65	22·48
ab	10·79	4·36	31·42
an	6·94	1·46	8·00
hy	1·54	0·84	0·10
il	0·69	0·48	0·18
mt	0·25	0·66	0·17
hm	0·66	—	1·12
C	2·58	4·46	0·60
ap	—	—	0·15
ru	—	—	0·27
	100·00	100·00	100·00

RE-CALCULATED NORMS (A.J.R.W.)

	1	2
Q	42·06	51·06
or	34·08	36·23
ab	10·93	4·49
an	7·73	1·45
hy	1·50	0·88
il	0·62	0·53
mt	0·13	0·05
hm	0·82	0·64
C	2·13	4·67
	100·00	100·00

NIGGLI VALUES

	1	2	3
qz	260	258	181
si	460	490	413
al	47	55	44
fm	11	9	12
c	12	3	11
alk	30	33	33
ti	1·6	1·4	1·0
k	0·74	0·89	0·40
mg	0·50	0·42	0·25

1. Shag Valley rock S 146/352243. Analyst F. T. Seelye (Benson, 1946, No. 11).
2. Shag Valley rock. Analyst F. T. Seelye (Benson, 1946, No. 12).
3. Average North Island ignimbrite calculated from 16 analyses given by Steiner (1958, Table 1, Nos 25 to 30, 32, 33, 35 to 40, 44, 45).

*A re-calculation of the norm of the Shag Valley rock (chem. analyses Nos 1 and 2) by one of the authors (A.J.R.W.) gives somewhat different values from those obtained by Benson.

CONCLUSIONS

The present investigation has shown that: (1) the Shag Valley acid igneous rock is an ignimbrite; (2) it is not a dyke but a surface rock interbedded with coal measures of Upper Senonian age.

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RADIOACTIVE BOULDERS IN HAWKS CRAG BRECCIA

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Summary

Several radioactive hornfels and granite boulders have been found scattered through the Hawks Crag Breccia in the Big River and Lower Buller Gorge areas. Uraninite has been identified in the radioactive biotite hornfels from the Lower Buller Gorge. An unidentified, iron-rich, uranium-bearing mineral occurs in the radioactive biotite hornfels from the Big River area. The radioactivity in the biotite granite from the Big River area is concentrated in the zircon and apatite inclusions and to a lesser extent in the biotite.

Two periods of uranium mineralization in the Paparoa Range area of the South Island of New Zealand are inferred; one in pre-Hawks Crag Breccia times, giving rise to mineralization in the basement rocks; and the second in post-Hawks Crag Breccia times, giving rise to the bedded coffinite deposits in the Hawks Crag Breccia.

INTRODUCTION

Bedded coffinite deposits in the Hawks Crag Breccia in the South Island of New Zealand have been described by Beck, Reed, and Willett (1958). Since that time, as a result of prospecting operations carried out by Buller Uranium Limited, radioactive boulders have been found in the Hawks Crag Breccia in the Big River (N.Z.M.S. 1, S 38) and Lower Buller Gorge (N.Z.M.S. 1, S 31) areas (Fig. 1). The purpose of this paper is to describe the mineralization in these boulders and to discuss their significance.

RADIOACTIVE BOULDERS FROM BIG RIVER AREA

The radioactivity in the Big River area is almost entirely confined to biotite hornfels and biotite granite boulders scattered through the Hawks Crag Breccia. In one locality, a lens of arkosic grit gives a count of × 3 background. The two radioactive boulders, both from Blacksand Creek (N.Z.M.S. 1, S 38), that have been examined are:

A. A biotite hornfels boulder (P 21265)

B. A biotite granite boulder (P 21066)

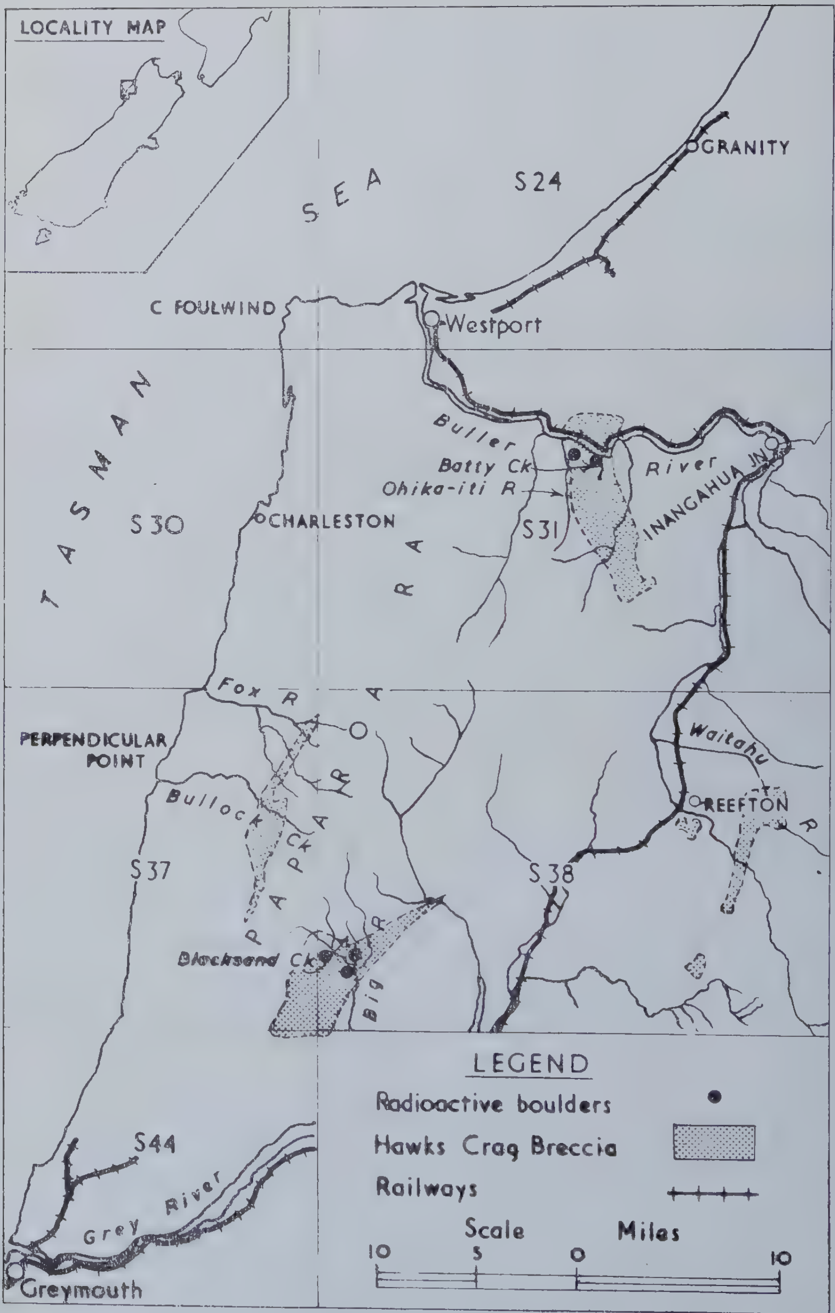

Fig. 1.—Map showing location of radioactive boulders in Hawks Crag Breccia.

A. Biotite Hornfels

The chief constituents of the biotite hornfels (P 21065) are quartz 60%, biotite 15%, muscovite 10%, chlorite 10%, and sericite 5% (Fig. 2). An opaque radioactive mineral, apatite, garnet, and tourmaline are present as accessory minerals. A quantitative chemical analysis for uranium and thorium shows that the rock contains 0·18% U_3O_8, while thorium was not detected. (Analysis by W. Kitts, Dominion Laboratory, D.S.I.R.)

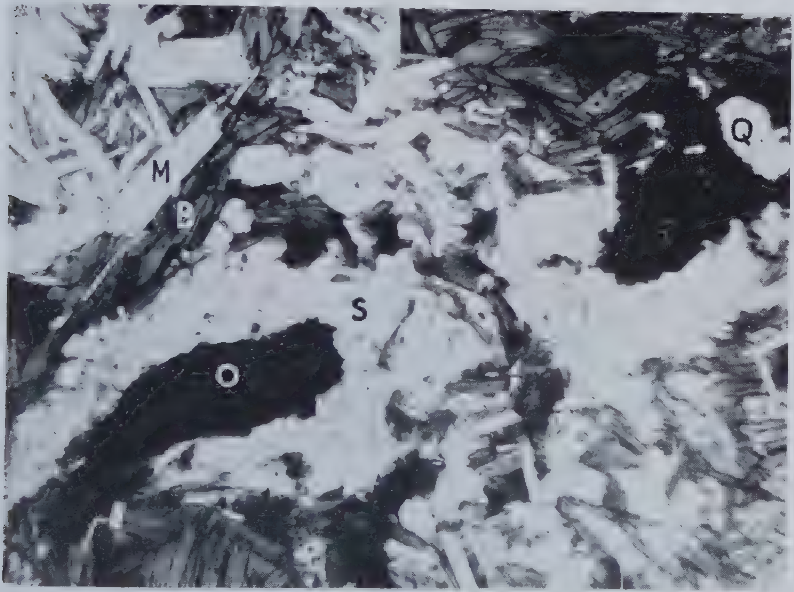

FIG. 2.—Photomicrograph of radioactive hornfels, P 21065 (ordinary light, × 46). B, biotite; M, muscovite; Q, quartz; S, sericite; O, ore minerals.
—*Photomicrograph by A. V. Weatherhead*

The rock has a schistose structure and is partly re-crystallized. The quartz shows undulose extinction. Biotite is occasionally seen to enclose grains of muscovite. The opaque radioactive mineral replaces biotite, muscovite, and chlorite. Associated with, and usually surrounding, the opaque radioactive mineral are plumose aggregates of sericite. Apatite inclusions occur in the biotite, muscovite, and chlorite grains. Tourmaline and garnet were not seen in thin section, but were found to be present in small quantities in heavy mineral concentrates.

By the use of heavy liquid separation techniques, a fraction consisting almost entirely of opaque ore minerals was obtained. The chief constituent of the heavy concentrate was the radioactive mineral, which has a steel-blue colour in reflected light and has a moderate to high reflectivity. Hematite and pyrite were present in the heavy concentrates as accessory minerals.

An X-ray powder pattern of the heavy concentrates is shown in Table 1, together with the powder patterns for hematite and pyrite. (X-ray analysis by Dr M. Fieldes and Dr L. D. Swindale, Soil Bureau, D.S.I.R.)

TABLE 1.—X-ray Powder Patterns of Heavy Concentrate from Sample P 21065, also of Hematite and Pyrites.

Heavy Concentrate		Hematite		Pyrite	
I	D	I	D	I	D
s	3·46	m	3·67	m	3·13
vs	2·70	vs	2·689	vs	2·71
w	2·49	s	2·508	s	2·42
s	2·42	m	2·198	s	2·21
m	2·32	m	1·833	m	1·918
w	2·22	s	1·688	vs	1·636
m	1·917	w	1·593	s	1·566
s	1·76	m	1·481	w	1·506
m	1·64	s	1·448	w	1·449
m	1·598				

The absence of some important lines for hematite and pyrite in the X-ray powder pattern of the heavy concentrate indicates that these minerals are present only in small quantities. The X-ray powder pattern of the heavy concentrate is thus considered to be essentially a pattern of an unidentified radioactive mineral. On heating the radioactive mineral to 1000° C overnight, an X-ray powder pattern showed that only hematite was present in a crystalline form.

The X-ray powder pattern for the radioactive mineral does not correspond to any mineral listed in the "X-ray Powder Data for Uranium and Thorium Minerals" (Fondel, Riska, and Fondel, 1956).

A semi-quantitative spectrographic analysis of the radioactive mineral gave results shown in Table 2. (Spectrographic analysis by H. J. Todd, Dominion Laboratory,D.S.I.R.)

TABLE 2.—Semi-quantitative Spectrographic Analysis of the Radioactive Mineral from Sample P 21065.

	%		%		%
Si	4·0	Mo	0·4	Sr	0·06
Al	1·0	Ni	0·4	Ba	3·0
Cu	4·0	Bi	0·05	Yr	0·01
Pb	0·4	As	0·07	Zr	0·05
Ti	2·0	Cd	0·004	U	1·5
Cr	1·5	Be	0·001	Th	0·2
Co	0·15	Sn	0·03	Fe	remainder
Mg	0·7	W	0·005		
Mn	0·08	Ca	0·3		

The radioactive mineral thus consists essentially of iron, while Si, Cu, Ba, Ti, U, and Cr are present in lesser quantities.

B. *Biotite Granite*

The radioactive biotite granite is coarse-grained, and contains about 20% dark minerals. It consists of strained quartz, perthitic orthoclase and microline, oligoclase, and biotite. The biotite is almost uniaxial, with Z = Y = 1·656, X = 1·591, B = 0·65. It is strongly pleochroic with Z and Y dark brown, and X light brown. The biotite is an iron-rich variety, probably approaching siderophyllite in composition. Apatite, zircon, hematite, and chlorite are present as accessory minerals. The apatites and zircons occur most frequently as inclusions in the biotite. These inclusions are commonly surrounded by pleochroic haloes. Hematite is usually present where the biotite has been altered to chlorite. Radiometric analysis of the rock showed that 0·025% eU_3O_8 is present.

A sample of the rock was crushed to — 422μ + 250μ and the biotite was separated from the quartz and feldspar by means of an electromagnetic separator. Part of the biotite fraction was then ground to — 62μ and the apatite, zircon, and iron ore separated by use of heavy liquids. The distribution of the radioactivity in various fractions was measured with a sensitive geiger counter (Table 3). (Radioactivity was measured by H. S. Jansen, Nuclear Sciences Division, D.S.I.R.) Each fraction was placed in turn in a cylindrical container, 2·41 cm in diameter and 0·72 cm in height. For the apatite-zircon-iron ore fraction, only 0·1 g of material was available. To measure the radioactivity of this fraction, the container was filled with sugar and the radioactive material sprinkled on the surface.

TABLE 3.—Distribution of Radioactivity in Granite Sample P 21066.

Fraction	Size (μ)	Composition	Rate (counts per min.)	Quantity of material used
A—Granite	—422 +250	Quartz feld. 80%, biotite 20%, + acces. apatite, zircon, chlorite, hematite	23·8	Full container
B—Biotite	—422 +250	Biotite and acces. zircon and apatite	132·8	Full container
C—Quartz and feldspar	—422 +250	Feld. 70%, quartz 30%, + acces. biotite, zircon, and apatite	23·9	Full container
D—Biotite	—62	Biotite	68	Full container
E—Apatite, zircon, iron ore	—62	Apatite 70%, zircon 20%, iron ore 10%	40	0·1 g
Empty container		—	0·8	none

From Table 3, it is evident that the radioactivity is most highly concentrated in the apatite-zircon-iron ore fraction (E), whilst the radioactivity of the biotite fraction (D) is almost three times as great as the granite as a whole (A). The fact that the radioactivity of the granite (A) and the quartz-feldspar fraction (C) are almost identical is difficult to account for. Since the quartz-feldspar fraction was separated from the biotite by the use of an electro-magnetic separator, any free grains of apatite and zircon were probably concentrated in the less magnetic, quartz-feldspar fraction, thereby increasing the degree of radioactivity of this fraction.

RADIOACTIVE BOULDERS FROM THE LOWER BULLER GORGE AREA

Although the radioactivity in the Lower Buller Gorge area is almost entirely confined to the bedded coffinite deposits, several radioactive biotite hornfels boulders have been found in the Hawks Crag Breccia. Boulder P 22059 A, from Batty Creek (N.Z.M.S. 1, S 31), has been examined by the writer.

The rock is a highly radioactive hematite-stained biotite hornfels. The sample can be divided into two parts: one portion being very strongly radioactive (1·7 eU_3O_8) and containing 50% of opaque ore minerals; the second portion being only weakly radioactive (0·2% eU_3O_8) and containing 1 to 2% of opaque ore minerals (Fig. 3). (Analyses by W. Kitts, Dominion Laboratory, D.S.I.R.)

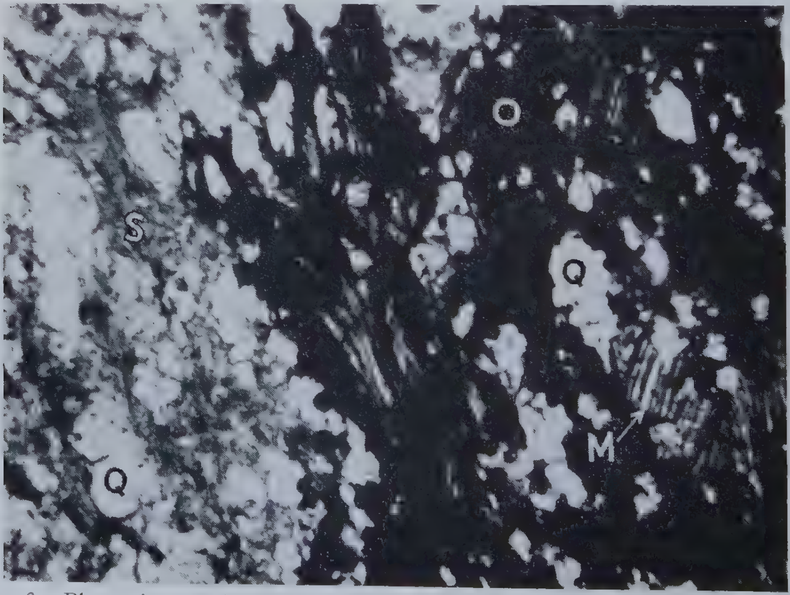

FIG. 3.—Photomicrograph of radioactive hornfels, P 22059 A, showing contact of highly and weakly mineralized portions of the sample (ordinary light, × 73). M, muscovite; Q, quartz; S, sericite; O, ore minerals.

—*Photomicrograph by A. V. Weatherhead*

The chief constituents of the highly radioactive portion are: opaque ore minerals including hematite 50%, quartz 40%, muscovite 8%, and biotite 2%. The ore minerals are replacing every mineral originally present in the rock.

The chief constituents of the weakly radioactive portion are: sericite 50%, quartz 40%, muscovite 5%, opaque ore minerals 2%, chlorite 2%, and biotite 1%. Apatite and zircon are present as accessory minerals in the sericite matrix, which is stained to a light-brown colour with a thin veneer of iron oxide. Opaque ore minerals are sparsely disseminated through the sericite.

The rock has a schistose structure and is partly re-crystallized. Thin veinlets of quartz cut across the schistosity of both the strongly and weakly radioactive portions of the sample at about 20°. The contact of the two portions of the sample is very sharp, and is sub-parallel to the schistosity.

A concentrate consisting of ore minerals, quartz, and accessory zircon, apatite, and biotite was obtained by the use of heavy liquid separation techniques. An X-ray powder pattern of the heavy concentrate (Table 4) showed that uraninite, hematite, and quartz were present. On heating the concentrate to 1000° C overnight, an X-ray powder pattern showed that the major constituents of the concentrate were hematite and U_3O_8 (Table 5) (X-ray analyses by L. D. Swindale, Soil Bureau, D.S.I.R.). A semi-quantitative spectrographic analysis of the heavy concentrate is shown in Table 6 (spectrographic analyses by H. J. Todd, Dominion Laboratory, D.S.I.R.).

TABLE 4.—X-ray Powder Pattern of Heavy Concentrates from Sample P 22059 A.

I	D	I	D
m	4·29	s	2·55
s	3·696	m	1·93
vs	3·36	m	1·85
s	3·14	s	1·83
vs	2·73	s	1·64
		m	1·61

TABLE 5.—X-ray Powder Pattern of Heavy Concentrates from Sample P 22059 A after Heat Treatment.

I	D	I	D
s	4·14	w	1·98
s	3·68	w	1·96
s	3·42	m	1·89
s	3·36	m	1·76
vs	2·71	s	1·69
s	2·64	w	1·59
vs	2·51	w	1·57
m	2·20	m	1·48
w	2·07	m	1·45

This is the first time that uraninite has been identified in New Zealand. The fact that it is associated with hematization adds weight to the generalization that uranium occurrences in New Zealand are associated with iron ores, particularly hematite.

TABLE 6.—Semi-quantitative Spectrographic Analysis of Heavy Concentrate from Sample P 22059 A.

	%		%		%
Si	15·0	Mo	0·01	Ca	0·8
Al	2·0	Ni	0·01	Sr	0·01
Cu	1·0	Bi	0·2	Ba	0·07
Pb	0·7	As	0·03	V	0·01
Ti	1·5	Cd	0·007	Yt	0·02
Cr	0·01	Be	0·01	Zr	0·7
Co	0·01	Sn	0·2	U	15·0
Mg	0·15	W	0·01	Th	0·4
Mn	0·02			Fe	remainder

AGE OF MINERALIZATION AND GENETIC SIGNIFICANCE OF THE RADIOACTIVE BOULDERS

Uranium mineralization of the radioactive boulders could have taken place either before or after their incorporation in the Hawks Crag Breccia. Strongly suggesting the first possibility are the following points:

(1) The scarcity and random distribution of the radioactive boulders in the Hawks Crag Breccia.

(2) The absence of evidence to indicate any association between the radioactive boulders and the bedded coffinite deposits.

(3) The variety of mineralization.

(4) The presence of uranium in Greenland Series and the Paparoa Granite-gneiss (Beck *et al.*, 1958, pp. 444–5) which are considered to be the source materials of the Hawks Crag Breccia.

(5) The lack of any appreciable alteration of the Hawks Crag Breccia surrounding the radioactive boulders.

It appears most likely, therefore, that two periods of uranium mineralization have occurred, one in pre-Hawks Crag Breccia times, giving rise to mineralization in the basement rocks; and a second period in post-Hawks Crag Breccia times, giving rise to the bedded coffinite deposits.

Pre-Hawks Crag Breccia Mineralization

The biotite hornfels occurring in the Hawks Crag Breccia in both the Big River and Lower Buller Gorge areas were formed by contact metamorphism of Greenland Series greywacke. The passage of uranium-bearing hydrothermal solutions through the hornfels caused alteration of some of the micas to sericite and the deposition of uranium-bearing minerals. There exists, therefore, a possibility of finding such a deposit *in situ*. The fact that the mineralized boulders have been subject to contact metamorphism suggests that the best area to search for such a deposit is in the vicinity of the granite-Greenland Series contact.

In the biotite granite boulders, the uranium is present in the common rock-forming minerals. This, and the absence of appreciable alteration, suggests that the uranium was already present during the crystallization or recrystallization of the granite. It appears likely, therefore, that the radioactive granite boulders originate from low-grade though perhaps extensive uranium-bearing granites.

Post-Hawks Crag Breccia Mineralization

The modified syngenetic and hydrothermal hypotheses for the origin of the bedded uranium deposits in New Zealand have been described by Beck *et al.* (1958, pp. 445–8).

The finding of the radioactive boulders in the Hawks Crag Breccia shows that uranium was present in the breccia when it was deposited. A syngenetic origin of the bedded deposits thus becomes a definite possibility. According to the modified syngenetic hypothesis, uranium originally scattered through the Hawks Crag Breccia in the Lower Buller Gorge has been concentrated into certain horizons during a period of very deep burial. In the Big River area, the presence of the radioactive boulders is in accordance with this hypothesis, as the Hawks Crag Breccia in this area was never deeply buried. In the Lower Buller Gorge, however, the presence of the highly radioactive uraninite-bearing boulders poses the question, why has the uranium not been leached out of these boulders whilst, according to the modified syngenetic hypothesis, it has been leached out of other boulders?

Further work will need to be done on the bedded deposits before a definite conclusion on their origin can be reached.

ACKNOWLEDGEMENTS

Grateful acknowledgements are made to Mr J. C. Braithwaite and Mr D. Bullen, of Buller Uranium Limited, whose prospecting activities revealed the radioactive occurrences just discussed.

The writer also wishes to express his gratitude to Dr J. J. Reed for his assistance and advice during the preparation of this paper.

Spectrographic analyses were carried out by Mr H. J. Todds, Dominion Laboratory, D.S.I.R. The chemical analyses were carried out by Mr W. Kitts, Dominion Laboratory, D.S.I.R. The X-ray powder data were supplied by Dr M. Fieldes and Dr L. D. Swindale, Soil Bureau, D.S.I.R., who also identified the mineral uraninite from these data. Radioactivity measurements were carried out by Mr H. S. Jansen, Nuclear Sciences Division, D.S.I.R. The photomicrographs were taken by Mr A. V. Weatherhead, New Zealand Geological Survey, D.S.I.R.

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SOME FIELD AND PETROGRAPHIC FEATURES OF AMERICAN AND NEW ZEALAND IGNIMBRITES

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(Received for publication, 3 February 1959)

Summary

In a study of some New Zealand and American ignimbrites (welded tuffs or ash-flow deposits), close similarities were found in the lithology and topographic relations of the deposits.

Lithic variations in rocks of ignimbrite origin are great, and even in a single sheet gradations from tuff to hard vitrophyre and felsitic rock are common. These gradations form a consistent pattern in the ignimbrites studied. They are illustrated in vertical sections and interpreted as due to differences in cooling environments.

Differences in the physical composition or texture and the relation to pre-existing topography of some ignimbrites provide clues to the diversity of pyroclastic flows which may exist.

Introduction

Well known features of ignimbrites are their extensive sheet-like form, tendency to form plateaus and prismatic-jointed cliffs, and the massive, unsorted nature of the rocks. Less understood have been such features as lithic variations, the significance of lenticular inclusions, their true areal extent, and the relationships of the deposits to pre-existing topography. A description and interpretation of the latter features are presented here in an attempt to provide a concise summary of facts that are fundamental to geologic investigations in ignimbrite country.

The information is based mainly upon the writer's recent and present research in the United States (Martin, 1957) and New Zealand. Observations were made and specimens collected during a summer of field work in ignimbrites for Dr E. F. Cook and Gulf Oil Corporation in Nevada, U.S.A. This was followed by about a year of laboratory study and more independent field study at the University of Idaho. The following 18 months were spent in New Zealand in a similar study. Many exposures in the "ignimbrite plateau" were visited, but field work was concentrated in the Maraetai area. Petrographic study has been made of surface-exposed specimens and numerous dam-site drill cores supplied by the Ministry of Works.

ORIGIN

Discussions here are based on the assumption that ignimbrites were formed by pyroclastic or *nuée ardente* type flows which were erupted as a highly mobile emulsion of incandescent ash, gas, and other pyroclastic material. This origin is widely accepted today and is fundamental to Marshall's (1932, 1935) definitions of ignimbrite.

The principal clues to the pyroclastic flow origin of ignimbrites were provided by studies of recent *nuée ardente* eruptions of Pelée and Soufrière in the West Indies and the "Katmaian tuff flow" in Alaska (Fenner, 1920). Although these eruptions produced relatively small and poorly indurated deposits compared with the great rhyolitic sheet ignimbrites of New Zealand and western North America, their related origin was soon recognized in New Zealand, Australia, and the United States (Marshall, 1932; Richards and Bryan, 1934; Mansfield and Ross, 1935).

Some authors have expressed the view that ignimbrites have formed from a type of lava flow (Grange, 1934, 1937) or froth flow (Kennedy, 1955). However, little sustaining evidence has been presented.

Probably the strongest evidence supporting the *nuée* or ash flow origin of these rocks is that all gradations can be seen between deposits of hard, lava-like rock and those of unconsolidated ash and lapilli of undoubted *nuée ardente* origin. Even within a single deposit, rock of obvious pyroclastic origin can be traced grading into a hard massive rock, the fragmental or clastic nature of which may be indicated only under the microscope. Further evidence supporting a pyroclastic flow origin is, of course, the great areal extent and sheet-like form of ignimbrites which suggest emplacement by a highly mobile and non-viscous mechanism, similar to observed *nuées*. The great mobility and transporting effectiveness of similar "fluidized" systems has been demonstrated in industry (Reynolds, 1954).

This argument is not meant to imply, however, that all ignimbrites were emplaced in exactly the same manner. In size, distribution, and physical characters, they are a highly variable group of rocks, and they may well represent equally varied types of eruptions. It was considered by Williams (1941, p. 279) "that between true lava and flows of gas-glass-dust emulsion there are all gradations".

Examples of some widely different deposits observed by the writer in New Zealand are the small *nuée ardente* pumice breccias at Atiamuri (Thompson, 1958, p. 289), the extensive and unconsolidated Taupo pumice breccia of the Rangitaiki-Taupo area (Baumgart and Healy, 1956), and several ignimbrites of different pumice content and degree of welding in the Mangakino area. Each of these examples has presumably been formed by a different type of pyroclastic flow.

TERMINOLOGY

Ignimbrite here refers to a stratigraphic volcanic unit, a pyroclastic deposit presumably of *nuée ardente* type eruption. The term has been used in this sense by its originator, Marshall (1935, pp. 331, 358), and has been recommended by Cook (1955). *Welded tuff, ash flow,* and *tuff flow* are currently used synonymously with ignimbrite by many writers.

Heterolithic refers to an originally uniform body of rock in which zones of physically different lithology or texture have developed due to differences in cooling environment.

Several texturally different types of rock commonly make up a heterolithic ignimbrite, and even greater differences in lithology may be found in different sheets, which may consist of material ranging from agglomerate to fine vitric tuff. Because of the great lithic variations in ignimbrites, such descriptive and generally non-genetic terms as *crystal tuff, tuff breccia* (Wentworth and Williams, 1932), *welded tuff, vitrophyre,* and *lenticulite* are used to identify particular rock types.

Pectinate refers to a comb-like development of acicular crystals from the margin of glass shards (Marshall, 1935, p. 359).

Eutaxitic refers here to a streaked appearance imparted by plane-parallel structures. Originally defined genetically as a type of flow structure, *eutaxitic* is now, according to the glossary of the American Geological Institute (1957), "most appropriately used in describing the structure of the majority of welded tuffs". The first application of the term *eutaxitic* to these rocks was by Iddings (1909, p. 331). Other terms which have been applied to this microscopic structure are: *flow structure* (Marshall, 1935, p. 349), *compact structure* (Gilbert, 1938, p. 1842), and *"ignimbrite" structure* (Westerveld, 1943, p. 208).

LITHOLOGY

Primary Constituents

Most ignimbrites are rhyolitic and hence similar in chemical composition, but, because of different modes of eruption, the texture and other physical properties of the rocks vary greatly. Primary constituents are of three types: vitric ash, intratelluric crystal fragments, and lithic fragments. These materials occur in different particle sizes, shapes, and proportions, and are easily recognizable, especially in non-welded tuff.

"Deuteric" Textural Changes

Further variation of the rocks is caused after eruption and during cooling by the welding and crystallization of vitric constituents. For example, in a non-welded ignimbrite such as that at the power house at Arapuni, a combination of vitric ash and pumic blocks forms a poorly undurated tuff-breccia, but in a more highly welded, thick ignimbrite the pumice and vitric shards may be welded and compressed to form a dense lenticulite such as the "owharoite" at Owharoa Siding. The degree of crystallization of the original vitric shards and pumice determines whether the rock is vitreous or lithoidal (stony) in appearance.

Even in a single ignimbrite, lithic variations, or facies, may be distinct, owing to differences in the local cooling environments of different parts of the deposit. This distinction is best developed in exceptionally thick and initially very hot deposits where great differences in pressure, temperature, and degree of retention of volatiles existed between the middle and edges, and top and bottom of the flow. In those deposits a consistent pattern of lithic zones is formed. Depending upon the presence or absence of these zones, ignimbrites may be divided into two groups:

(1) Poorly zoned ignimbrites, which are either non-welded or contain a single hyaline welded zone.

(2) Heterolithic ignimbrites, which contain distinct zones, or facies, of differing lithology.

POORLY ZONED IGNIMBRITES

The poorly zoned ignimbrites are mainly thin deposits less than 100 ft thick, commonly containing abundant pumice lapilli or blocks. They may be entirely porous and non-welded, such as the Peruvian sillars (Fenner, 1948), or they may contain a welded zone in the middle as in the upper ignimbrite at Arapuni, and the Rattlesnake tuff of Oregon, U.S.A. Examples of non-welded ignimbrites are abundant in the area between Mangakino and the Waipapa Hydroelectric Station, New Zealand. All these deposits differ from the heterolithic ignimbrites in that the tuffaceous nature of the rock can be recognized throughout; even in a welded zone, the glass shards are but weakly devitrified and commonly are plainly visible.

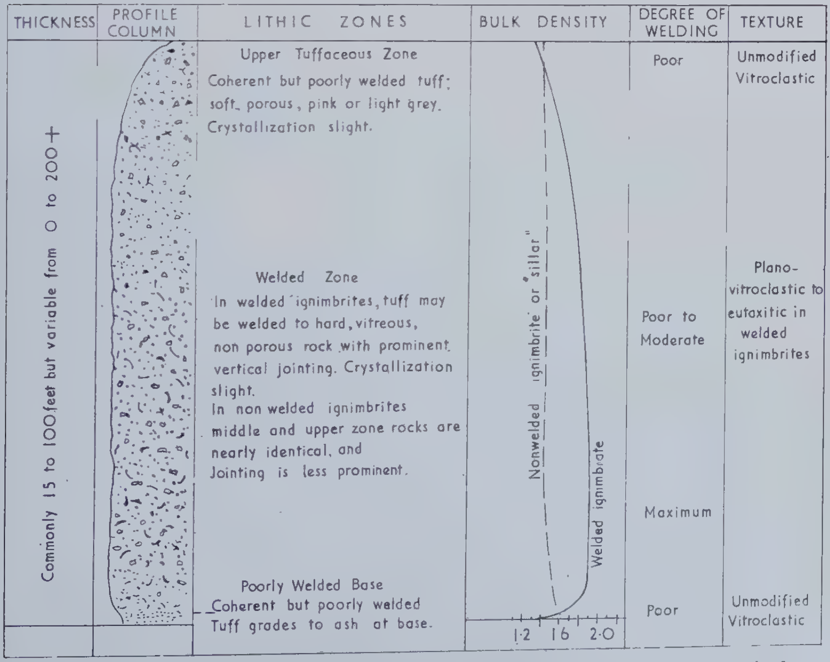
THICKNESS
PROFILE COLUMN
LITHIC ZONES
BULK DENSITY
DEGREE OF WELDING
TEXTURE
Commonly 15 to 100 feet but variable from 0 to 200+
Upper Tuffaceous Zone
Coherent but poorly welded tuff; soft, porous, pink or light grey. Crystallization slight.
Welded Zone
In welded ignimbrites, tuff may be welded to hard, vitreous, non porous rock with prominent vertical jointing. Crystallization slight.
In non welded ignimbrites middle and upper zone rocks are nearly identical, and Jointing is less prominent.
Poorly Welded Base
Coherent but poorly welded Tuff grades to ash at base.
Nonwelded ignimbrite or "sillar"
Welded ignimbrate
1·2
1·6
2·0
Poor
Poor to Moderate
Maximum
Poor
Unmodified Vitroclastic
Plano-vitroclastic to eutaxitic in welded ignimbrites
Unmodified Vitroclastic

FIG. 1.—Lithic properties as seen in a vertical section through a typical poorly zoned or non-heterolithic ignimbrite.

Some physical properties through a vertical section of such a deposit are summarized in Fig. 1. High density and resistance to erosion of the welded zone in the middle and lower part of the ignimbrite are indicated by the bulk density curve* and profile column respectively. The tuff may be so highly welded here that it has a vitreous lustre and conchoidal fracture, but the constituent glass and pumice fragments are still recognizable in the rock face and in thin section.

The effects of compaction are best developed in the lower part of the welded zone. There the once hot and viscous glass shards are commonly flattened and bent around harder crystal and rock fragments, producing a eutaxitic structure (Fig. 6).

At the base of the ignimbrite the density, hardness, and erosional resistance of the rock decreases abruptly as the welded tuff grades into a zone of ash. The latter represents a zone which was quickly chilled before welding and viscous compaction could occur. A similar but more gradational zone makes up the uppermost part of the ignimbrite. In both zones the tuff is pulverulent and generally has an unmodified vitroclastic structure (Fig. 7).

Devitrification is weakly developed in these ignimbrites. The finer grained dust of the matrix is commonly cryptocrystalline and surrounds pumice and glass shards which are either holohyaline or slightly devitrified (pectinate) at their margins.

HETEROLITHIC IGNIMBRITES

General Features

The heterolithic ignimbrites contain two or more zones of markedly different lithology. They generally represent thicker,† hotter, and more slowly cooled deposits than the poorly zoned ignimbrites. Consequently, they are more compact and highly crystallized. Quickly chilled parts of both types of ignimbrites are tuffaceous and hyaline.

Vertical variations of a typical heterolithic ignimbrite are represented graphically in Fig. 2. The data, and that in Fig. 1, are based upon the writer's studies in New Zealand and the United States (Martin, 1957), and agree basically with the results of a similar study by Bailey (1957).

The profile column (Fig. 2) represents a typical cliff outcrop with poorly welded, non-resistant zones at the top and bottom of the sheet, and vertical jointing in the welded portion. Other non-resistant layers may exist in the welded zone if porous spherulitic and lithophysal structures are abundant. These porous zones are also indicated by fluctuations in the bulk density curve, which generally shows a gradual increase downward to the poorly welded basal zone, where there is an abrupt decrease in density.

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*For thin, non-welded ignimbrites, the curve is almost straight, with density nearly constant from top to bottom (Martin, 1957, p. 70).

†Thickness is highly variable in ignimbrites, and great depth of burial is helpful, but not essential to form highly welded or heterolithic zones, provided the newly deposited ash is hot and viscous enough to weld and crystallize. Enlows (1955, p. 1228) described such an ignimbrite only 30 in. thick.

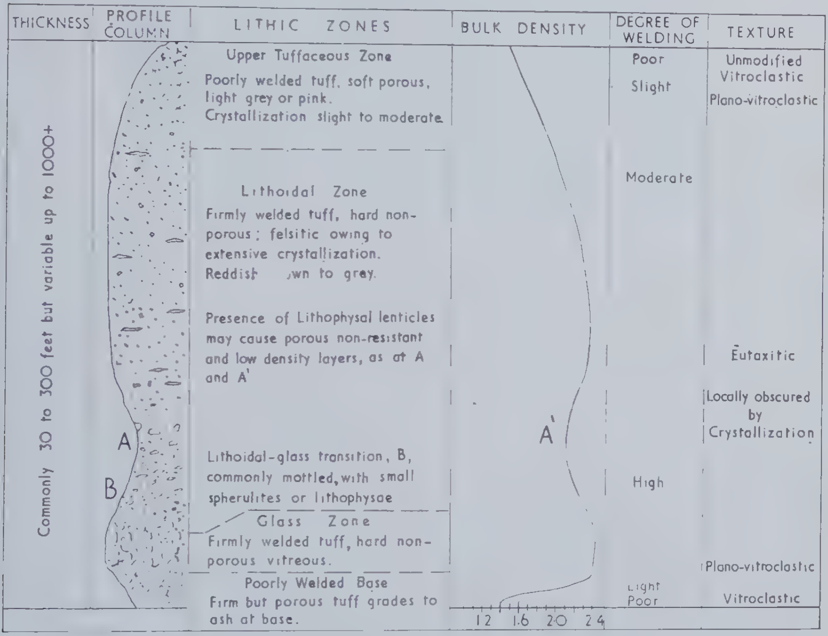
THICKNESS
PROFILE COLUMN
LITHIC ZONES
BULK DENSITY
DEGREE OF WELDING
TEXTURE
Commonly 30 to 300 feet but variable up to 1000+
Upper Tuffaceous Zone
Poorly welded tuff, soft porous, light grey or pink. Crystallization slight to moderate
Lithoidal Zone
Firmly welded tuff, hard non-porous; felsitic owing to extensive crystallization. Reddish brown to grey.
Presence of Lithophysal lenticles may cause porous non-resistant and low density layers, as at A and A'
A
B
Lithoidal-glass transition, B, commonly mottled, with small spherulites or lithophysae
Glass Zone
Firmly welded tuff, hard non-porous vitreous.
Poorly Welded Base
Firm but porous tuff grades to ash at base.
A'
1.2
1.6
2.0
2.4
Poor
Slight
Moderate
High
Light
Poor
Unmodified Vitroclastic
Plano-vitroclastic
Eutaxitic
Locally obscured by Crystallization
Plano-vitroclastic
Vitroclastic

FIG. 2.—Vertical lithic variations of a typical heterolithic ignimbrite.

Poorly Welded Upper Zone

The upper zone of such an ignimbrite consists of poorly welded tuff that is generally light pink or grey, porous, and relatively soft. It has a vitroclastic structure (Fig. 3), which shows little or no effect of compression, and in which the glass shards are slightly pectinate.

Welding and crystallization are poorly developed in this upper zone mainly because of rapid heat loss at the upper surface of the newly deposited sheet, and, as pointed out by Marshall (1935, p. 339) and Gilbert (1938, p. 1849), the lack of compressive force which exists lower in the deposit.

Lithoidal Zone

The tuff increases in hardness, density, and degree of welding downward as it passes into a lithoidal zone of hard minutely crystallized felsitic rock (Figs 4, 5). This zone makes up the bulk of most heterolithic ignimbrites. It is commonly composed of reddish-brown or grey

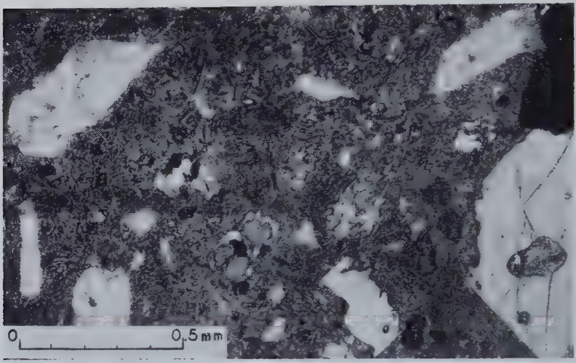

FIG. 3.—Non-welded tuff from the upper zone of an ignimbrite at Maraetai. Note pectinate shards and resorbed intratelluric quartz crystal. Plane light.

welded tuff containing intratelluric crystals or phenocrysts which give it the appearance of porphyritic flow rock. In thin section the rock has a eutaxitic structure which may be obscured locally where crystallization has been intense. This zone is interpreted (Gilbert, 1938, p. 1856) as that part of the deposit which retained its heat longest, allowing maximum crystallization and welding. It corresponds roughly with the "pectinate phase" of Marshall (1935, p. 359).

At the base of the lithoidal zone in some ignimbrites is a dark transitional layer between the lithoidal and glassy zones. Here the matrix is partially hyaline, but contains abundant spherulitic or lithophysal structures. In some ignimbrites, such as one exposed in the southern Pancake Range, Nevada, a zone of small brown spherulites and opaque crystallites cloud the glass; in others devitrified spherules with gaping gas cavities predominate, as shown in drill cores from the Waipapa dam site, New Zealand. Marshall (1935, p. 359) referred to this part of an ignimbrite as the "radial phase".

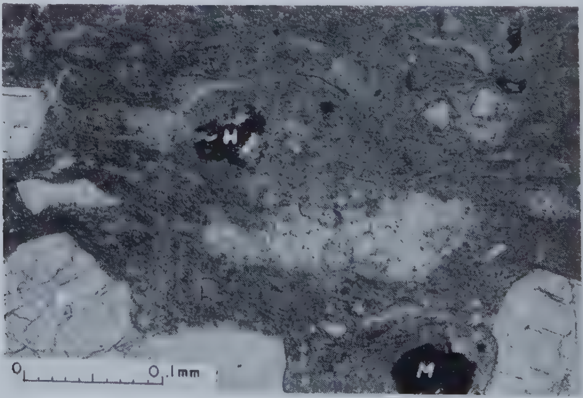

FIG. 4.—Eutaxitic structure in lithoidal welded tuff from Waipapa. Near the middle is a crystallized relict pumice fragment. Plane light.

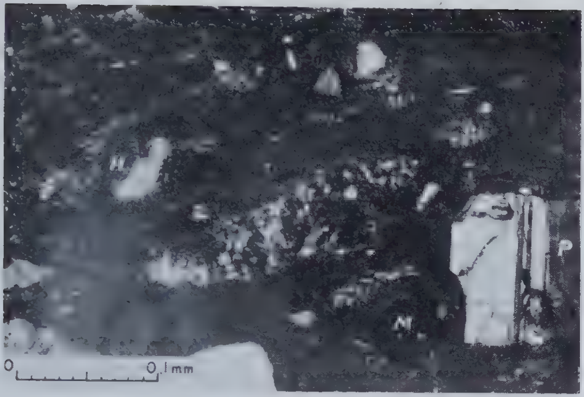

FIG. 5.—Same view as Fig. 4, showing extent of crystallization. Note contrast between fine grain deutetric crystobalite and albite, and the larger intratelluric crystals (plagioclase, magnetite, hornblende). Crossed nicols.

Glassy Zone

A glassy zone, commonly of shiny black vitrophyre, is almost ubiquitous beneath the lithoidal zone in heterolithic ignimbrites. Microscopically (Fig. 6), its matrix is typically holohyaline and has pronounced eutaxitic structure, but in the field the glass resembles structureless porphyritic obsidian, and commonly has a granular or crumbly quality because of abundant perlitic cracks. The glass zone represents part of the chilled base of ignimbrites where the vitric shards were hot and viscous enough to be compressed into a tightly welded mass by the overburden of tuff, yet were cooled before crystallization could occur (Gilbert, 1938, p. 1856).

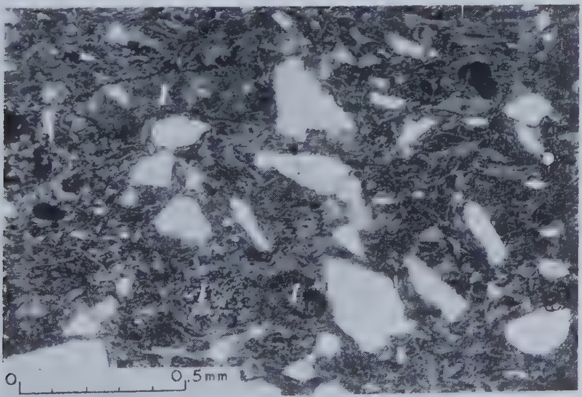

FIG. 6.—Moderate eutaxitic structure in black vitrophyre near base of the Maraetai ignimbrite. Note the three foreign inclusions. Plane light

Basal Zone

As in the poorly welded ignimbrites, the glassy welded tuff decreases abruptly in hardness and degree of welding as it grades downward into a layer of non-welded tuff or ash at the base (Figs 7, 8). This layer varies from less than 1 in. to more than 10 ft in thickness. The ash is commonly light grey, free of devitrification, and presumably resembles the material in the parent pyroclastic flow more closely than any other part of the ignimbrite. Marshall (1935, p. 337) described a layer of "fine sand" 3 in. thick at the base of an ignimbrite and interpreted it as "the portion of the fiery cloud that was cooled rapidly by contact with the atmosphere and the ground".

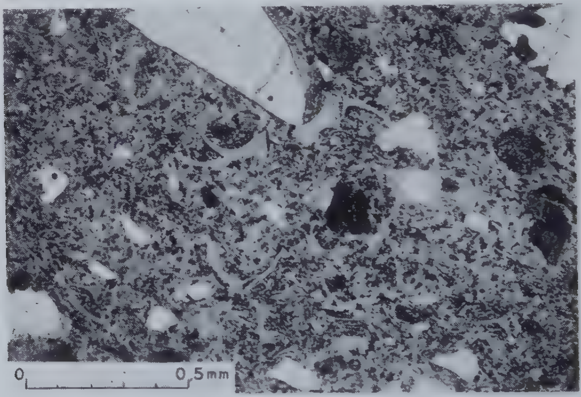

FIG. 7.—Unmodified vitroclastic structure of non-welded tuff just 5 ft below that of Fig. 6. The change in structure from Figs 6 to 7 is gradational, as it is from Figs 3 to 7.

The non-welded basal zone is absent in some ignimbrites. In Meadow Valley, Nevada, the writer observed a few ignimbrites welded at the base, and apparently all of those reported by Enlows (1955) in Arizona have a welded base. These are presumably the product of exceptionally hot ash flows poured over a dry surface of low thermal capacity and conductivity. It is possible, too, that a welded base is formed in areas near the source of eruption where the ground is pre-heated by the continued passage of the hot ash flow before deposition begins (Martin, 1957).

PETROGRAPHIC FEATURES

Structures

The gradation from loose vitroclastic structure in the upper and basal zones to eutaxitic in the welded portion has been described. True contorted flow banding in ignimbrites has not been recorded, but some exceptional outcrops with long streaky "fluidal" banding may be seen. Those observed have been planar structures and were probably produced by compaction at temperatures unusually high for ignimbrites.

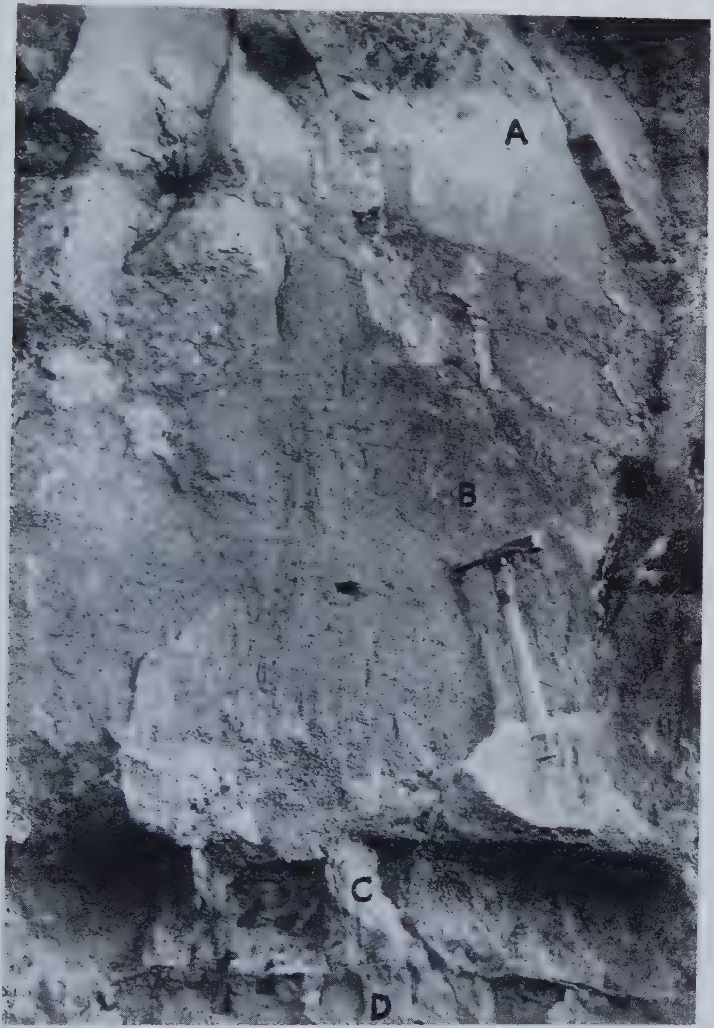

FIG. 8.—Poorly welded base of an ignimbrite near Mangakino. (A) Highly welded tuff containing black glass lenticules (welded pumice lapilli); (B) soft lightly welded tuff; (C) ash base resting on (D) sediments.

Crystal Constituents

Crystals in welded tuffs are of two types: intratelluric crystals or phenocrysts, which formed before eruption, and deuteric crystals which formed *in situ* while the rock cooled. The intratelluric crystals, commonly quartz, feldspar, and mafic minerals, are more conspicuous, for they commonly exceed 1 mm in length, and comprise up to 45% or more of the volume of the rock.

The deuteric or devitrification minerals are commonly a combination of silica and feldspar. Some which have been recorded are: tridymite-orthoclase or natrosanidine (Fenner, 1948), tridymite-sanidine (Gilbert, 1938), tridymite-albite (Westerveld, 1943), and quartz-sanidine (Enlows, 1955). Pneumatolytic cristobalite, feldspar, magnetite, and hornblende were found by Bailey (1957). Similar combinations, including cristobalite and albite, have been observed by the writer (Fig. 5).

These minerals are generally microscopic or submicroscopic; only in some porous cavities and spherulites are they seen with the naked eye. The crystallization takes place in several ways, resulting in pectinate structures or simply in a turbid cryptocrystalline aggregate in the dust surrounding glass shards. Where crystallization is well developed, irregular radial growths are common and platy microlites are scattered abundantly through the matrix or concentrated within pectinate glass shards and lithophysal cavities. In most ignimbrites, well-formed spherulites are not common, but in some they may be abundant, especially in the lithoidal-glass transition zone near the base.

The crystallization has occurred mainly at high temperature while the deposit cooled. Evidence that normal temperature devitrification has apparently been negligible is the non-devitrified glass matrix in the chilled portions, particularly the base, of most of the ignimbrites studied.

AUTOPNEUMATOLYSIS

The role of rising gases as an aid to crystallization has been emphasized by many early workers (Fenner, 1920; Gilbert, 1938; Marshall, 1935). Large quantities of volatile matter, chiefly water vapour, are released as the glass cools and crystallizes. Evidence that gases have acted as metasomatic or catalytic agents in ignimbrites has been given by Bailey (1957) and by Gilbert (1938). The latter author reports the presence of crystallized glass fragments and rimmed feldspar crystals in the relatively cool upper portions, and development of a "crystalline horizon well above the middle of the tuff". On the other hand, Enlows (1955) found no evidence of pneumatolysis in some Arizona welded tuffs and concluded that the process is of local importance only.

Although pneumatolysis is doubtless active in some ignimbrites, it is apparently lacking in others. A few of the ignimbrites examined by the writer shows some development of pneumatolytic crystals or feldspar rims, but others, particularly thin sheets, do not. An evaluation of this type of crystallization based upon the presence of feldspar rims and the crystallinity of the upper part of ignimbrites is often complicated by the fact that the high permeability of the upper zone allows alteration of the tuff by downward moving weathering solutions as well as by upward moving gases.

LENTICLES IN WELDED TUFF

Abundant lenticular inclusions are a conspicuous feature of some ignimbrites. The lenticles are commonly about 1 in. long, and may be glassy, stony, or porous and crystalline. They have generally been interpreted (Marshall, 1935; Gilbert, 1938; Enlows, 1955) as flattened lithic fragments, but the writer has found that some are the result of intense local crystallization in the tuff (Martin, 1957). They are considered here as two types:

(1) collapsed pumice lenticles, formed of flattened and welded glass and pumice lapilli; and

(2) lithophysal lenticles, formed by crystallization in local pockets.

Collapsed Pumice Lenticles

The collapsed pumice lenticles are far more abundant than the crystalline or lithophysal lenticles, and are more uniform in size and shape. Like the tuff in which they are embedded, they may have been altered by varying degrees of compaction and crystallization. Thus, in non-weld tuff, pumice lapilli are generally irregular in shape and randomly oriented. In lightly welded tuff, elongate lapilli may be oriented to form a planar fabric, yet may not appear to have been flattened or welded (Fig. 9a). In more highly welded tuff, the pumice is progressively more collapsed (Fig. 10), so that extremely compressed and welded fragments take the form of lenticles of black glass (Fig. 9b). In the lithoidal zone of ignimbrites, the lenticles are devitrified and may have a stony appearance (Fig. 9c).

Relict pumice lenticles are abundant in ignimbrites of lithic tuff, especially in the most welded portion near the base. Here a glassy lenticulite may form, as exposed in a thin zone at Putaruru (Marshall, 1935, p. 359) and in California, two miles west of the Mono Craters. Foreign inclusions of previously consolidated non-vitric rock such as andesite or sandstone commonly remain angular and undeformed side by side with the collapsed pumice lenticles (Fig. 9c).

Lithophysal Lenticles

The other type of lenticles in ignimbrites are crystalline bodies analogous to lithophysae and crystalline flow bands in acid lavas. These bodies vary from small spherules to thin discoids which form parallel to the base of the ignimbrite. The latter may range in size from microscopic to several feet in diameter (Martin, 1957). The spherules, where more highly developed, may be irregular in shape and enclose lenticular cavities (Fig. 9d). Spherules of this type from Waipapa (Fig. 9d) are essentially devitrification balls developed in the upper part of the glassy zone. They resemble the rock of the lithoidal zone microscopically and macroscopically, and may, by confluence and exclusion of the surrounding glassy base, grade into the lithoidal rock above.

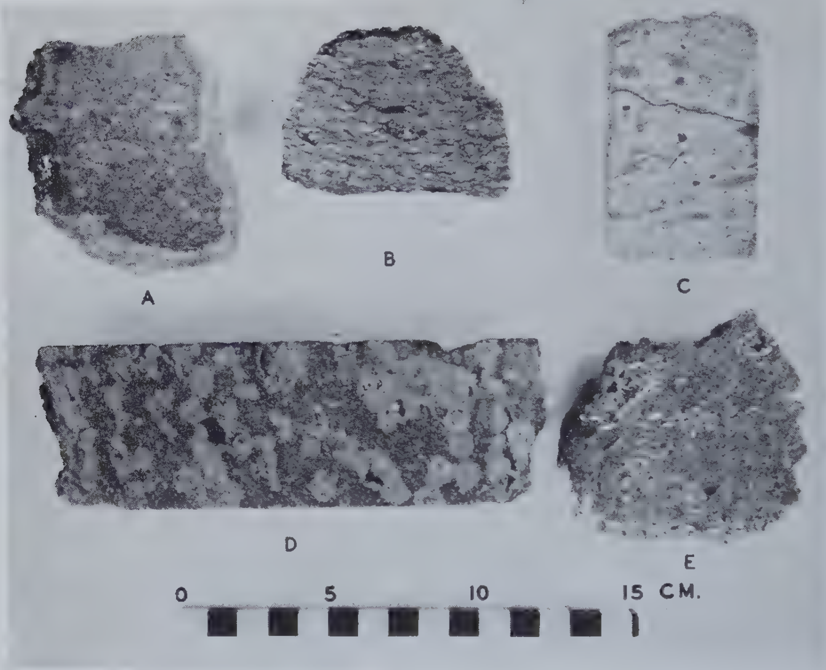

FIG. 9.—Several types of lenticulite:
(A) Partially collapsed pumice lapilli from Marshall's Lookout, Mangakino.
(B) Black glass lenticles in a specimen of the Bishop tuff, California, U.S.A.
(C) Collapsed and devitrified pumice lapilli in welded tuff from a drill core at Waipapa. Small angular grains are undeformed andesite fragments.
(D) Coalesced devitrification spherules and associated gas cavities. From the upper part of the glassy zone of an ignimbrite at Waipapa.
(E) Poorly formed lithophysal lenticles in lithoidal welded tuff from an exposure north of Hiko, Nevada, U.S.A.

—*M. D. King, photo.*

Thinner lenticles and irregular lithophysal bodies (Fig. 9e) may develop anywhere in the lithoidal zone. These are more coarsely crystalline and contain microcrystalline quartz, tridymite, feldspar, and related minerals. They are apparently the result of localized crystallization, the discoidal bodies growing parallel to the eutaxitic structure. Differential weathering of the lithophysal lenticles produces pockmarked or slitted outcrops which characterize some ignimbrites.

Determination of Origin

In some welded tuffs, it is difficult to determine if the origin of crystalline lenticles is due to lithophysal crystallization of the matrix as described, or to complete devitrification of collapsed pumice fragments. One means of distinguishing the two types is to consider the

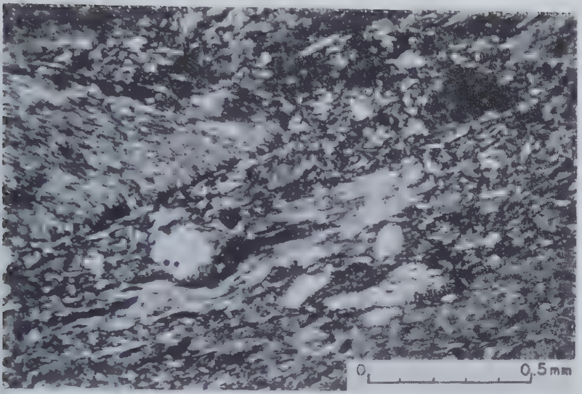

FIG. 10.—Wedge and brush-like terminations of partially collapsed pumice fragments. Specimen is "owharoite" type lenticulite (Grange, 1937, p. 59) from Owharoa Falls, New Zealand.

distribution of pumice fragments in the ignimbrite as evidenced by the poorly welded material above and below the zone of lenticles. If fragments of pumice of about the same size and abundance as the lenticles are scattered elsewhere in the deposit, it may be assumed that the lenticles are relict pumice fragments. If, on the other hand, the ignimbrite is of fine-grained tuff with only sparse pumice fragments, any large or abundant lenticles may be assumed to be lithophysal or primary crystallization features.

This means of identifying lenticle origin assumes that pumice fragments are always distributed uniformly throughout ignimbrites. This is not so, for a certain degree of sorting of large and small fragments can often be found. Where such sorting or concentration of pumice fragments has been observed in poorly welded ignimbrites, however, they are conspicuous in the upper part of the deposit.

Shape is not a positive criterion for the interpretation of thin or regular lenticles, but spheroidal or irregular shaped bodies are much more likely to be lithophysal than relict pumice. Pumice fragments, when compressed, form fairly uniform lenticles which may have wedge-shaped or abrupt brush-like terminations in thin section (Fig. 10).

AREAL EXTENT

The great extent and sheet-like nature of ignimbrites is in contrast to the dome-like form of acid lava flows. The mobility which some pyroclastic flows must have had may be deduced from the account and map of Mansfield and Ross (1935, p. 309). Two distinctive sections of a presumably continuous welded tuff deposit are described from south-east Idaho, U.S.A. The two sections are approximately 65 miles apart in a north-east-south-west direction. Mansfield states that the material seems to increase in thickness to the north-east, and that the material was probably erupted from that direction—in the Yellowstone Park area. If this is so, this sheet-like deposit must well exceed 100 miles in linear extent.

More conclusive evidence of the extensiveness of ignimbrites, and of the colossal nature of the eruptions which produced them has been found by Cook and Mackin in the south-west United States. In a volcanic stratigraphy study, Cook (1958) reported: "Individual units have been traced 100 miles linearly; some of these units probably had an original extent of more than 5,000 square miles . . . At least one unit is more than 1,000 ft thick, but the average thickness is about 200 feet."

RELATION TO PRE-EXISTING TOPOGRAPHY

Conflicting reports exist regarding the effects of topography on pyroclastic flows. Many accounts of the glowing avalanches of the West Indies and studies of the Katmaian "tuff flow" (Fenner, 1920) and the Bishop tuff (Gilbert, 1938) have led to the impression that ignimbrites are generally restricted to valleys and depressions near their source of eruption.

Nevertheless, a few isolated accounts to the contrary have been reported by Mansfield (Mansfield and Ross, 1935, p. 309), who described "ducoed" welded tuff covering ridges and valleys alike with little change in thickness; by Dustan (Sahni and Dunstan, 1920, p. 5), who stated: "The deposits [the Brisbane tuff, Australia] evidently were not laid down as mud, as the tops of the hills were as thickly covered as the bottoms of the valleys"; and by Marwick (1946, p. 74), who found similar evidence in some New Zealand ignimbrites.

MOBILITY OF PYROCLASTIC FLOWS

Examination of some very extensive ignimbrites of varied lithology and structural features leads the author to the conclusion that the horizontal and vertical mobility of a pyroclastic flow depends to a great extent upon its mechanical composition (fragment size distribution) and heat content. Assuming other factors, such as vapour pressure of the magma and the size of the eruption to be equal, *hot gaseous flows of finely comminuted ash are more mobile than flows choked with heavy crystal and lithic material.*

Ignimbrite eruptions of great masses of relatively high-density crystal-vitric ash, or those heavily laden with lithic fragments apparently produce immense *ash flows* which tend to be restricted by moderate topographic barriers, yet may pour over large areas mainly by virtue of their great bulk and gravitational energy. The Maraetai ignimbrite of the North Island appears to have been formed by such a flow. The areal extent of the deposit is not yet known, but its former massive fluidity is shown where it butts against high ridges, and completely buries surfaces of low relief.

Eruption of very hot liquid magma containing only sparse crystals or other inclusions may produce great *glowing clouds* of fine vitric ash dispersed in extremely hot gas. These gaseous clouds are of low density and have great horizontal and vertical mobility. Mansfield's "ducoed" welded tuff appears to have been deposited by such a cloud. It is a thin deposit of highly welded vitric shards with only sparse and very small crystal and pumice fragments. The Rattlesnake tuff of Oregon and some of the thin, extensive ignimbrites of south-east Nevada are similar in thickness and physical composition, and probably were deposited in this manner.

COMPARISON OF NEW ZEALAND AND AMERICAN IGNIMBRITES

Some obvious relationships of the New Zealand and western North American ignimbrites have been noted and some tentative comparisons can be made. The comparisons are limited specifically to the ignimbrites of eastern Nevada, U.S.A., and those of central North Island, New Zealand. The former rocks may prove to be typical of, or genetically integrated with, the large bodies of pyroclastic rocks covering much of Nevada, Utah, Arizona, and Mexico.

The most striking difference between the ignimbrites of these areas is their manner of exposure or appearance in the field. Those of the Basin-Range province in Nevada are boldly exposed on massive fault scarps where an arid climate allows little vegetation or soil development. The ignimbrites are of mid-Tertiary age (Cook, 1958), and the even surfaces of tilted fault blocks are commonly bare and have been stripped of younger sheets by erosion. The New Zealand ignimbrites are, by comparison, poorly exposed in an area of generally moderate relief, recent ash showers, and abundant vegetation. They are Plio-Pleistocene (Grange, 1937) deposits, the youngest of which still retain remnants of their upper surfaces. They are capped here and there by rhyolite domes and by more widespread beds of ash and pumice. Deformation and denudation have been slight, and outcrops of the older sheets are rare.

Petrologically, the ignimbrites of Nevada and New Zealand are very similar. Both are rhyolitic rocks of normal calc-alkaline series, and are associated with lavas of dacite, andesite, and basalt. In New Zealand, the volume ratio of acid rocks to intermediate and basic rocks is about 9 to 1 (Clark, 1957). In Nevada, the ratio is of the same order. Also, rocks of ignimbrite origin greatly predominate over obvious flow rocks. Block faulting is evident in both areas, but associated ash-shower pyroclastics are rare in eastern Nevada.

Mineralogically, both groups of ignimbrites contain abundant intratelluric quartz, plagioclase, and minor hornblende, but the North Island volcanics are characterized by a sparsity of sanidine and a dominance of hypersthene over biotite and monoclinic pyroxene. The American ignimbrites studied are more potassic, with sanidine and biotite as common constituents. Plagioclase varies from oligoclase to labradorite, and andesine was observed frequently in both areas.

More similarities than differences exist lithologically. A higher proportion of the observed New Zealand ignimbrites consist of lithic tuff, hence there is a wide variety of collapsed pumice lenticulites. No ignimbrites characterized by thin, regular, lithophysal lenticles were seen, however. In Nevada, many of the deposits are more vitric and tightly welded. Lenticulites are less common than in New Zealand.

Unconformities between ignimbrites are present in both areas, but are not conspicuous. In Nevada, once the initial topography was buried by the early volcanics, succeeding ash and lava flows poured over flat terrain to produce a stratified series of volcanic sheets, chiefly ignimbrites. Between the individual units only local evidence of folding or erosion is observed, despite the fact that the eruptions spanned a long period of Eocene to Pliocene time.

In New Zealand, similar features are observed, but the period of volcanicity is as yet short, perhaps only one million years. The individual sheets are generally thin, and appear to have been erupted at fairly short intervals, but at least one marked unconformity is evident. This erosion surface at Mangakino is of considerable relief and separates petrographically dissimilar ignimbrites, indicating that there was at least one significant break in the rhyolitic volcanism of that area.

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PETROGRAPHY OF THE WHAKAPAPANUI GORGE ANDESITES, MOUNT RUAPEHU

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Summary

Petrological study of the andesite lavas exposed in Whakapapanui Gorge on the northern slopes of Mt. Ruapehu reveals constant mineralogical composition of flows. All are porphyritic andesites with phenocrysts of plagioclase, hypersthene, and augite set in a hyalopilitic groundmass. Slight variations in texture sometimes occur between and within flows of lava.

INTRODUCTION

Mt. Ruapehu is an andesite volcano reaching a height of 9175 ft above sea-level and rising about 6000 ft above a surrounding volcanic plateau. It is one of a group which includes the active cone of Ngaurahoe and the active craters of Tongariro. The lavas emitted by those volcanoes have been referred to as andesites (Grange, 1937) and the group is situated near the south-west extremity of a zone of active volcanism that extends north-eastwards to White Island in the Bay of Plenty.

Little detailed petrological work has been published on Ruapehu rocks. Early references to trachyte, phonolite, and other rock types (e.g. Crawford, 1868; Cussen, 1886; Park, 1886 and 1887; Hill, 1891 and 1895) have not been substantiated by later workers. Thomas (1887) referred to augite-andesites, and Hutton (1889) in an early microscopic study recorded hornblende-andesite, augite-andesite, and enstatite-hypersthene-augite andesite. Apart from the hornblende-andesite referred to by Hutton (1889), Speight (1908) and Professor R. H. Clark (pers. comm.), no volcanic rock other than hypersthene-augite andesite is known to the writer.

This study aims to record petrographic details of typical Ruapehu andesites at a particular locality, and to ascertain whether or not variation exists within, or between successive lavas. The area borders the Whakapapanui stream on the northern slopes of Mt. Ruapehu and extends from an altitude of about 5400 ft to 6400 ft above sea-level.

PHYSIOGRAPHY AND STRATIGRAPHY OF WHAKAPAPANUI GORGE

Mt. Ruapehu is dissected by radial consequent streams which have acted on its stratified lavas and ashes to produce a structural escarpment and terrace type of landscape Cotton, 1944, pp. 375-6). One such

N.Z. J. Geol. Geophys. 2 : 412-20.

stream, the Whakapapanui, cuts through more than eleven flows which now give rise to waterfalls and form terraced cliffs along its valley (Fig. 2).

The oldest lavas and agglomerates of that valley (the "Pinnacle Lavas") were once extensive, and were eroded into an earlier valley by some precursor of the present stream. Later flows here named the "Whakapapanui Lavas" largely filled the early valley, butting against and overlapping the eroded Pinnacle Lavas. Recent erosion has cut through both the younger and older formations, and the outcropping edges of a number of flows can be observed in the Whakapapanui Gorge and in places the Whakapapanui Lavas are obviously unconformable on the Pinnacle Formation (Figs 1 and 3). Recent ash, alluvium, and talus which occur in gentler depressions and at the base of cliffs rest unconformably on all earlier formations.

PETROGRAPHY OF THE WHAKAPAPANUI LAVAS

Megascopically, the flows of the Whakapapanui Lavas are similar and all are porphyritic andesites. Massive lava is remarkably fresh, but the scoriaceous materials are often weathered to a rusty brown or red coloured rock. Most flows are of a uniform medium grey colour. Vesicles, when present, are irregular in shape and size and are not lined with secondary minerals. Flow structures are not obvious or common, but curved shrinkage joints occur in some flows. The groundmass is glassy to very fine grained, so that the whitish tabular phenocrysts of plagioclase are conspicuous. Blocky prisms of pyroxene are also present, being more conspicuous in some flows than in others.

Microscopically, the rocks consist of phenocrysts of plagioclase, augite, hypersthene, and small magnetites set in a sub-vitreous to hyalopilitic groundmass. Between the feldspathic microlites of the groundmass, there is a relatively large amount of brown glass, giving the hyalopilitic texture which appears to be characteristic of the Ruapehu andesites. Throughout the groundmass occur small specks of black iron ore, probably magnetite, along with tiny crystals of clinopyroxene. Apatite occurs as an accessory mineral also, both in the groundmass and as small inclusions in feldspar phenocrysts.

In flow 9 (O'Shea, 1957) phenocrysts are set in a groundmass consisting almost entirely of dark brown or grey glass showing only incipient crystallization. Small light coloured patches (flow 8) which are clearly visible in some hand specimens, indicate portions of the groundmass where some crystallization has occurred. The boundaries between these glassy and partly crystalline groundmasses are extremely sharp in some sections (Fig. 4). In some flows there are more microlites than usual in the groundmass and the texture may be described as intersertal.

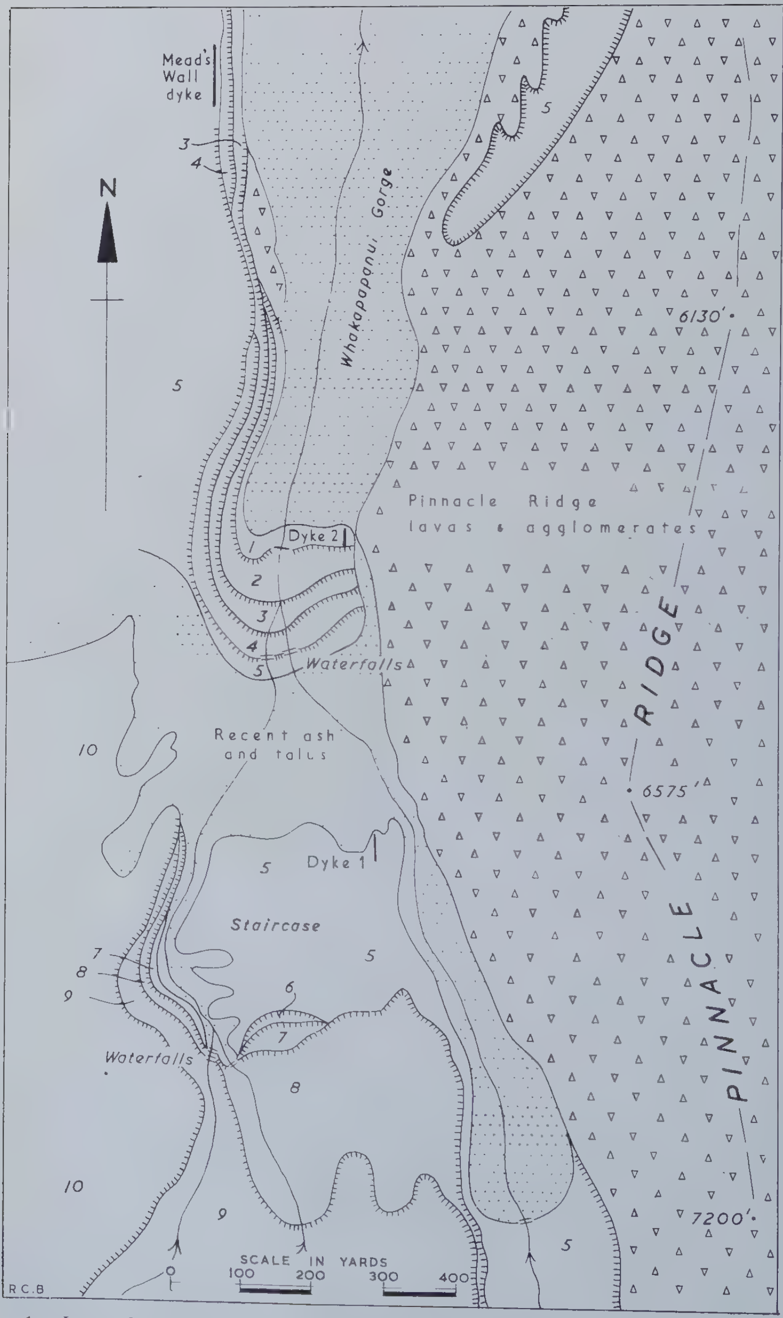

FIG. 1.—Lava flows of the Whakapapanui Gorge, Mt. Ruapehu. Based on Lands and Survey Map of Mountain Hut area. Whakapapanui lavas are numbered in ascending order, and basal contacts of flows are hachured.

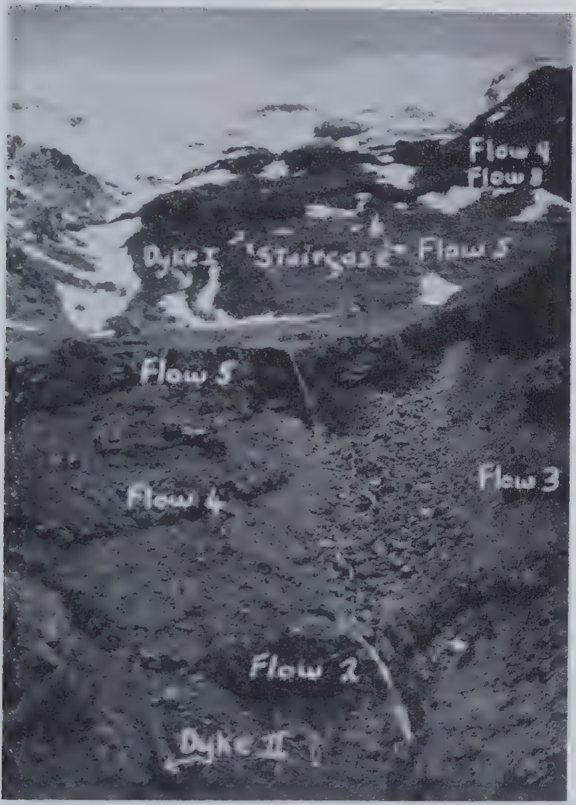

FIG. 2.—Amphitheatre-like head of the Whakapapanui Gorge showing flows, Dyke 1 and Dyke 2.

Plagioclase

Plagioclase feldspar occurs as subhedral tabular crystals varying considerably in size down to the lath-shaped feldspar microlites of the groundmass. The largest feldspar phenocryst observed measured 2·3 mm by 0·75 mm, but the average size is considerably less and varies slightly in different flows. The feldspar microlites measure about 0·02 mm or less in length, and in places show marked fluidal arrangement. The plagioclase phenocrysts are the dominant phenocrysts in the rock and their composition varies from An_{62} to An_{68} (basic labradorite). Zoning of the plagioclase phenocrysts is common and both normal and oscillatory zoning was observed.

Inclusions of brown glass are found in most phenocrysts although in some sections they are rare. Commonly they are rather large, oval or irregular, and are uniformly distributed throughout the crystal. They are, as a rule, aligned parallel to the crystal boundaries. Resorp-

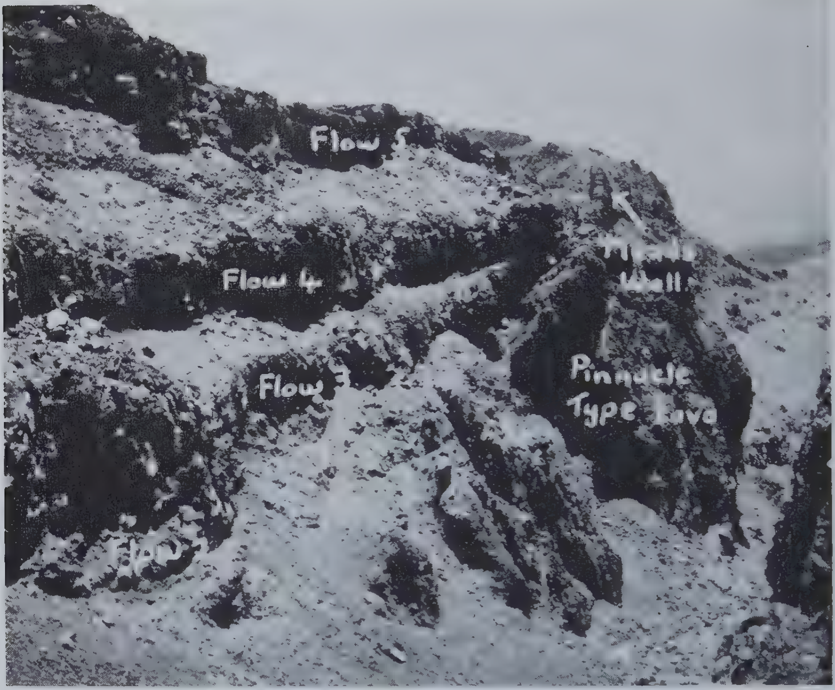

FIG. 3.—Left bank of Whakapapanui Gorge showing Mead's Wall Dyke and flow outcrops.

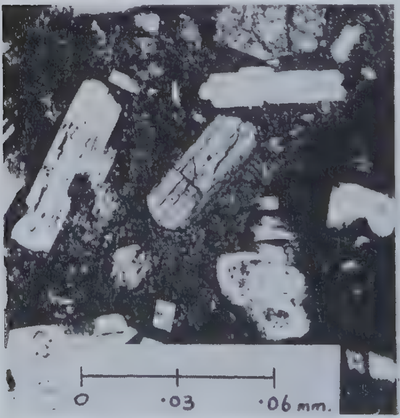

FIG. 4.—Photomicrograph of two groundmass textures within the same section. Typical Ruapehu hyalopilitic texture on left and less common glass groundmass on right. Note sharp boundary. Plane polarized light—Section 10,061—Flow 8

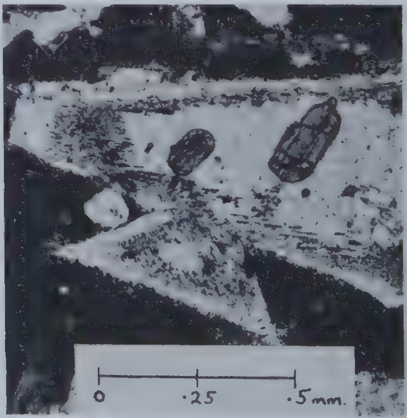

FIG. 5.—Photomicrograph of a plagioclase phenocryst with two hypersthene inclusions. Note narrow inner zone of glass inclusions. Plane polarized light—Section 10,053—Flow 5.

tion and corrosion of the original crystal has occasionally occurred, and a clear outer border indicates that later enlargement of the feldspar has ensued. Sometimes the inclusions are confined to a narrow zone inside that margin. In addition, one large plagioclase phenocryst possesses two hypersthene inclusions (Fig. 5). In general, the andesites with a more crystalline groundmass have a greater proportion of glass inclusions in the feldspars than the andesites with a less crystalline groundmass.

Other inclusions observed are a few small hypersthenes, augite, and a few very small apatites and iron ore. In the Whakapapanui flows, what appear to be xenolithic aggregates of feldspar crystals are common. A typical xenolith (Section 10053 Geol. Ref. Coll'n. V.U.W.) measures 1·7 mm and is composed of small granules of feldspar 0·02 mm or more in diameter. An inclusion of radiating lath-shaped crystals of wollastonite (Section 10,050), encircled by quartz grains of about 0·17 mm diameter, appears to be similar to the wollastonite inclusion described by Battey (1949).

Pyroxenes

Pyroxenes occur as subhedral phenocrysts of hypersthene and augite. Hypersthene phenocrysts tend to have a prismatic habit, although some are irregular in shape and they vary in size. Often, small phenocrysts of hypersthene and plagioclase are associated together in an irregular fashion to form a clot, or glomeroporphyritic aggregate, of hypersthene and plagioclase (Fig. 6). $2V_x$ was determined as 60° ± 2° in most flows although 66° ± 2° was recorded: these values indicate roughly 56% to 64% enstatite (Winchell, 1951, p. 218). A zoned hypersthene measured 62° in the inner zone and 69° in the outer zone, indicating a change in composition from about 58% to 68% enstatite. Pleochroism from pale green to pale brown or red is distinct.

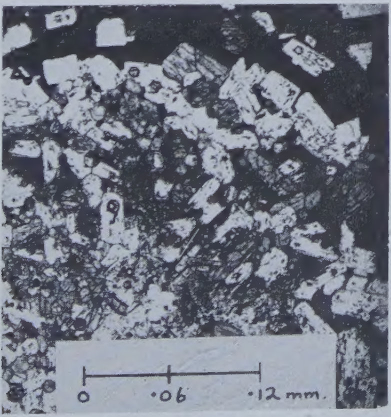

FIG. 6.—Photomicrograph of aggregate of hypersthene and plagioclase crystals. Plane polarized light—Section 10,050—Flow 5.

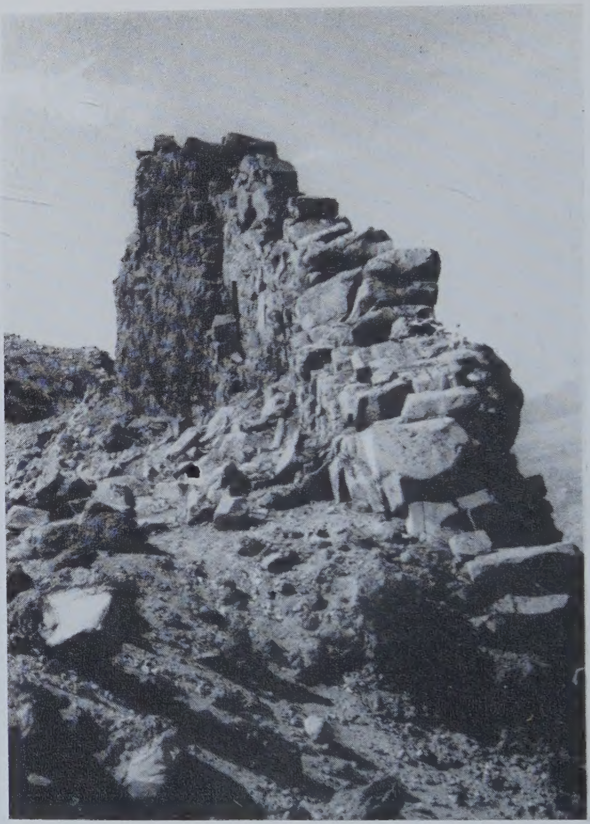

FIG. 7.—Mead's Wall Dyke.

Augite has a similar habit, and although it usually occurs as separate crystals, glomerophenocrysts of considerable size are fairly common. Crystals are about 0·3 mm in diameter ranging down to smaller crystals 0·05 mm in diameter. Conspicuous zoning was observed in one crystal (Section 10,047), augite forming the core and hypersthene the mantle. The augite is pale brown in colour and slight pleochroism is sometimes seen. Twinning was observed in many cases.

Optic properties are as follows:—

$Z \wedge c = 45°$, although $41\frac{1}{2}$ was also recorded.
$2V_z = 50° \pm 2°$.
$\beta = 1{\cdot}685$ to $1{\cdot}69$.

The composition of the augite, as determined from curves of Hess (1949), is that of diopsidic augite, $Ca_{42}\,Mg_{44}\,Fe_{14}$.

Iron Ore

Iron ore, probably magnetite, occurs as scattered, irregularly-shaped grains in the groundmass and as small crystals, also of irregular shape. Sometimes a few larger irregular grains are associated with pyroxenes.

INTRUSIONS IN THE WHAKAPAPANUI FLOWS

Only three minor intrusions, dykes with north-south strike, were observed in the area studied. The largest dyke, Mead's Wall (Figs 3 and 7), is of slightly lighter grey colour than the andesites and is fairly coarse grained. Petrographically it is little different from the flows it intrudes, except that the pyroxene phenocrysts are noticeably large. Dyke 1 is considerably smaller (Fig. 2) and is similar to the Whakapapanui flows. A conspicuous xenolith (Section 10,085) of feldspar granules with associated biotite and magnetite was observed. Dyke 2 is the smallest of the three. The groundmass, which is dark grey and very fine grained, includes large white phenocrysts of feldspar, some measuring about 3 mm by 1 mm. The groundmass predominates and the numerous feldspar microlites are usually up to 0·08 mm. The few phenocrysts present are very large and are usually aggregated to form glomerophenocrysts. One such aggregate of pyroxenes and plagioclase measured 3·3 mm in diameter. Oval-shaped vesicles show rough fluidal tendencies and there is little or no magnetite.

PINNACLE LAVAS

The Pinnacle lava flows are generally a little lighter in colour and coarser in grain than the Whakapapanui lavas. The flows, together with associated agglomerate, are particularly well exposed on Pinnacle Ridge (Fig. 3). The microlites and the phenocrysts in the groundmass are generally larger and more numerous than in the Whakapapanui flows and the rock is more crystalline. $2V_x$ for hypersthene is somewhat higher than 76°, indicating a composition of at least 74% enstatite. $2V_z$ for augite is $50° \pm 2°$ as in the flows, but some $Z \wedge c$ measurements showed $32\frac{1}{2}°$ instead of the more usual 45°. A reaction rim around a xenocryst of quartz was observed showing evidence of reaction between the quartz and andesite lava. The quartz is surrounded by a zone of brown glass which in turn is encircled by a zone of small augite prisms (Section 10,081).

CONCLUSION

Within a representative area of Mount Ruapehu there appears to be little mineralogical variation between or within flows of two recent eruptive cycles. All are porphyritic augite-hypersthene andesites with essentially the same mineralogical composition.

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